Force Appreciation, Perceived Function and Physical Performance in Surgically Stabilised Shoulders for Recurrent Anterior Instability

Pradnya Prakash Gadkari

A thesis submitted to Auckland University of Technology in partial fulfilment of the requirements for the degree of Master of Health Science (MHSc)

April 2023

School of Clinical Sciences
Health and Rehabilitation Research Institute

Abstract

Objective

To examine whether force appreciation at the affected shoulder after anterior stabilisation surgery is significantly different from the unaffected shoulder at 6-12 months from surgery. To investigate the relationship between force appreciation and perceived function and physical performance tests.

Study Design

A cross-sectional inter-limb comparison study with participants at 6-12 months after anterior stabilisation surgery.

Background

In New Zealand each year, 25% of individuals with shoulder dislocations require anterior stabilisation surgery to prevent recurrences and improve shoulder stability. However, the instability rate after surgery may range between 3% - 89%. It is thought that decreased neuromuscular control at the shoulder could be contributing to episodes of instability post-surgery. Proprioception influences neuromuscular control and force appreciation is a construct of this modality. It is unknown whether force appreciation differs between affected and unaffected shoulders in a post-surgery cohort. It is possible that decreased force appreciation at the affected shoulder could affect neuromuscular control and dynamic stability and may predispose to instability episodes.

Method

Twenty-five participants with an anterior stabilisation surgical procedure for recurrent anterior instability were recruited. Force appreciation at the affected and unaffected shoulder was examined with the shoulder at 90^{o} abduction and external rotation. The dependent variables were force accuracy and force steadiness. Statistical comparisons (paired t-tests) were made between the affected and unaffected shoulders. Perceived function was examined using Western Ontario Shoulder Instability Index (WOSI), ROWE, Shoulder Instability-Return to Sport after Injury (SI-RSI) and Tampa Scale of Kinesophobia (TSK). Physical performance across shoulders was assessed using SARTS tests. Correlation coefficients were utilised to assess the relationship between force appreciation variables with perceived function and with one physical performance test (BABER).

Results

There was a significant ($p < .05$) difference in force steadiness for external rotators between the affected shoulder (mean: 5.5 SD = 2.3) and unaffected shoulder (mean: 4.6 SD = 1.4). The force steadiness for internal rotators was significantly ($p < .05$) greater at the affected shoulder (mean: 2.8 SD = .64) in comparison to the unaffected (mean: 3.1 SD = .76) shoulder.

Concerning associations, the results showed that those individuals with higher LSIs for force accuracy in external rotators had higher perceived function (K- Tau = -.34), as measured by the WOSI. Similarly significant associations were observed for force accuracy (K-Tau = .32) and force steadiness (K-tau = .34) LSIs of the internal rotators with perceived function as measured by the ROWE.

Conclusion

The observed mean deficit of 0.9 % of target torque for force steadiness of external rotators across limbs was statistically significant, but its clinical relevance is questionable. Similarly, the deficit of 0.3 % of target torque for force steadiness of internal rotators was significant but negligible hence thought to be not clinically relevant. These results do not provide the impetus to change clinical practice, but they provide a starting point upon which further research that targets different measures related to force appreciation could be undertaken.

Regarding associations, the findings highlight that improved force appreciation is associated with improved perceived function, but individually, the variables tested contribute to a small proportion of change in perceived function. It is likely that a larger study allowing multiple variables to be incorporated within a model would be a valuable next step.

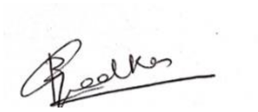
Table of Contents

List of Figures

List of Tables

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.



18 April, 2023

Signature

Date

Acknowledgements

This research project has been a long journey, and I would like to mention a few people here who have supported me to reach the finish line. I am sincerely thankful to my supervisor Prof. Peter McNair for the wisdom, guidance, and encouragement he has given me throughout this project. Peter, you nudged me the right direction during our discussions about the thesis content and this helped to bring clarity in the writing of the thesis. I have acquired new knowledge, answered some key questions, and most importantly learnt a lot about myself. I have discovered my strengths, weakness and above all realised that I have the tenacity to do research.

I am thankful to my dear colleague and friend Dr. Margie Olds, who encouraged me to embark on this journey. I have learnt a lot from her, and our discussions on shoulder related topics stimulate me to think differently. Thank you lending me the equipment that I needed for my project and for taking the time to read and critique my thesis.

Thank you to Mr. Robert Elliot, and Mr. Stewart Walsh for their help in participant recruitment. Their steady referrals of participants kept up the momentum for the testing phase of the project which suffered in its fledgling phase due to the COVID pandemic.

I am thankful to all the participants who gave their valuable time and came for testing at AUT. Without them this research project could not have gone ahead.

Thank you to Julie Balloch (Postgraduate and Research coordinator,) for your prompt responses regarding all administrative queries. It was reassuring knowing that you handled the administration side which otherwise would have been a tedious task to navigate by myself.

I am grateful to Physiotherapy New Zealand for their financial scholarship. And to have the support of my dear friends Tania and Louise in Auckland, and other friends overseas. Thank you for being empathetic listeners and encouraging me in moments when the challenge was on, and I couldn’t see the light at the end of the tunnel.

Most importantly, I am grateful to my husband Nakul, my children Sahana and Nevan for their love, kindness, and support that they have given to me in the last two years. Nakul, you have held the fort patiently, while I neglected the home front a little bit and worked on my thesis. Your contribution in bringing finesse to my thesis has been extremely valuable. Both Sahana and Nevan have been my cheer squad, silently carrying on with their schoolwork without demanding any more of my time and attention during the final phase of the thesis completion. To Anjali, my dear sister-in-law, thank you for proofreading my thesis, I really appreciate it.

Lastly, a special thanks to my parents living in India, although they were oblivious to the mundane matters of my research project, they always believed that I could achieve my goals with hard work and determination. Their unconditional love and blessings have always carried me forward in life.

When I first embarked on this journey, it was with trepidation. Now it has sparked an interest in research for which I am grateful.

Chapter 1 Introduction

1.1 Statement of the Problem

It is reported in literature that approximately 95% of anterior shoulder dislocations result from traumatic injury. It is more frequent in the young athletic population, especially those engaged in contact and collision type of sports such as rugby and football (Dodson & Cordasco, 2008; Mohammed et al., 2015).The overall incidence rate reported in literature is 24 per 100,000 person-years with higher incidence rate in young men (98 per 100, 000 years) (Olds et al., 2015). In males under 45 years, 5,606 shoulder dislocation injuries were reported in New Zealand from April 2019 to March 2020. Of these, 1,421 injuries required surgical stabilisation. The total cost to the health service in New Zealand for these claims over this period was almost NZ$ 17 million (ACC analytics, personal communication, June 30th, 2022). In addition, time off work/school adds to financial costs and burden of the condition. Furthermore, the emotional impact of this injury on an individual can also be profound and long lasting (Olds et al., 2015).

Traumatic anterior dislocation of shoulder most often damages the anterior joint capsule and disrupts the anterior band of the inferior glenohumeral ligament (Provencher et al., 2021). In addition, there can be detachment of anterior inferior labrum resulting in a Bankart tear or a defect in the contour of the anterior inferior glenoid also known as bony Bankart lesion (Cordasco et al., 2020; Dumont et al., 2011; Ogawa et al., 2006; Owens et al., 2010). Along with the capsuloligamentous structures, the subscapularis muscle also restrains anterior translation of humeral head on the glenoid during abduction and external rotation and it is likely that traumatic anterior shoulder dislocation could result in injury to this musculotendinous unit (Turkel et al., 1981). Thereafter, the defect in glenoid labrum decreases the depth of the glenoid socket in anteroposterior direction, increases the translation of humeral head on the glenoid by 20% when subjected to compression forces, and decreases the surface area of contact between humeral head and glenoid (Itoigawa & Itoi, 2016). Ultimately, this can notably reduce the inherent structural stability of the glenohumeral joint.

A higher incidence rate of osteoarthritis has been reported with delay between the initial dislocation to surgery (Brophy & Marx, 2005; Ogawa et al., 2006). The high recurrence rate of 10% - 90% after an initial dislocation adds to the complexity of the problem (Brophy & Marx, 2005). Hence shoulder stabilisation surgery is often recommended to reduce the recurrence of dislocation in younger athletes and allow them to return to sports more safely (Dodson & Cordasco, 2008; Galvin et al., 2017). Surgery for anterior shoulder instability can include arthroscopic /open repair of glenoid labrum or a Latarjet procedure. The latter is an open/arthroscopic procedure and involves transferring the coracoid bone block to the antero-inferior part of the glenoid (Boileau et al., 2010; Caubère et al., 2017).

The management of athletes in high-risk sports with recurrent anterior instability is contentious, but it is reported in literature that surgery is more effective than conservative treatment to allow a safe return to sports (Dumont et al., 2011; Elsenbeck & Dickens, 2017; Levy et al., 2016; Mattern et al., 2018). Unfortunately, some individuals continue to experience shoulder instability on return to play or sports even after surgery. The recurrence rate of shoulder instability after anterior stabilisation surgery varies between 3% - 89% (Hurley et al., 2019; Mattern et al., 2018). Some individuals experience fear of re-injury and decreased perceived function after stabilisation surgery which prevents them from returning to sports at pre-injury level (Hurley et al., 2021; Lädermann et al., 2016; Tjong et al., 2015). Micro-instability of glenohumeral joint can persist after surgery and may be contributing to a feeling of instability, and apprehension (Lädermann et al., 2016). Although exact mechanisms causing this micro-instability are unclear, it has been proposed that deficits in proprioception, inhibition of central nervous system or changes in specific areas of the brain leading to reorganisation of functional connectivity could be causing recurrent instability and apprehension (Cunningham et al., 2015; Lädermann et al., 2016). (Cunningham et al., 2015). Based on this research it appears that although surgery restores the structural integrity of the shoulder joint, some individuals continue to experience feelings or sensations of instability. A better understanding of other factors involved in maintaining glenohumeral joint stability is required.

Both static and dynamic restraints contribute to glenohumeral joint stability. The static restraints include glenohumeral joint capsule, ligaments, glenoid labrum, and bony geometry. The dynamic restraint mechanism involves muscle activation and force production by the shoulder joint muscles. The sensorimotor system mediates the interplay between this static and dynamic restraint systems (Myers et al., 2006). This system involves multiple sensors (visual, auditory, proprioceptive), motor component (muscles) and the integration and processing of this information occurs in the central nervous system. The output from this control system influences the dynamic stability at shoulder joint and is termed ‘neuromuscular control’ (Jones, 2014; Myers et al., 2006).

For many years, examination of shoulder muscle activation and strength, and its contribution to dynamic stability at the shoulder has been the focus of the research in shoulder instability population (Edouard et al., 2011, 2013; Lee et al., 2020). However, proprioception also influences neuromuscular control. It encompasses joint position sense, kinaesthesia, sense of force, effort and heaviness (Myers et al., 2006; Proske & Gandevia, 2012). Joint position sense has been well researched in unstable shoulders and studies have highlighted that deficits persist in operated shoulders even at 6-12 months from surgery (Fremerey et al., 2006; Pötzl et al., 2004; Rokito et al., 2010; Zuckerman et al., 2003). One such study showed a correlation between joint position sense deficit and return to previous sporting level after surgery (Fremerey et al., 2006).

Force sense is defined as our ability to perceive and respond to forces applied and generated across a joint (Myers et al., 2006; Proske & Gandevia, 2012). One method to study force appreciation is to examine the accuracy and steadiness of force generation by asking subjects to match or track a target force as closely as possible. Using such tests, disturbances in force appreciation are found after joint injuries (Bandholm et al., 2006; Docherty & Arnold, 2008; Perraton et al., 2013, 2017; Sousa et al., 2017; Telianidis et al., 2014; Ward et al., 2019). At the shoulder joint, force steadiness was found to be impaired at submaximal target force for concentric shoulder abduction in individuals with shoulder pain (Bandholm, 2006), and in rotator cuff tendinopathy (Maenhout et al., 2012). Poor force appreciation could contribute to altered neuromuscular control and as such, under estimation of required muscle force for a task can amplify existing joint instability. So far, there are no such studies which have investigated force appreciation after anterior stabilisation shoulder surgery and examined whether this is associated with perceived function, fear of movement and the ability to return to sports.

1.2 Purpose of the Study

The purpose of the study was twofold:

1. Primary aim was to examine and compare force appreciation at the affected and unaffected shoulder in individuals who have undergone anterior stabilisation surgery and are at 6-12 months post-surgery. It was hypothesized that force appreciation would be decreased for shoulder internal and external rotators in the affected shoulder at this time point after anterior stabilization surgery.

2. Secondary aim was to investigate if there is a relationship between force appreciation variables and perceived shoulder function and physical performance tests for return to sports. It was hypothesized that those individuals with decreased force appreciation would have decreased levels of function and quality of life and lower scores on the physical performance test.

1.3 Significance of the Problem

The results of this study may be relevant for health professionals who are involved in rehabilitation of individuals after anterior shoulder stabilisation surgery. This might enhance their understanding regarding the role of force appreciation in neuromuscular control at the shoulder joint following anterior stabilisation surgery. Potentially it may further lead to developing methods to examine this clinically at the early stages of rehabilitation and include techniques to improve force appreciation. It may also provide information about the relationship between force appreciation deficits and perceived function and physical performance tests for return to sports. Any correlation observed between force appreciation and perceived function may encourage health professionals to address this component in early stages of rehabilitation.

Chapter 2 Literature Review

2.1 Introduction

This chapter is divided into eight sections. It begins with description of the search strategy used for the literature review. This is followed by an outline of the concept ‘dynamic stability’ and its role in anterior glenohumeral joint instability. The fourth section is an overview of proprioception, specifically force appreciation and examination of the terminology used in defining force appreciation. The fifth section outlines the various methods used to examine force appreciation in humans. The current understanding of force appreciation in healthy individuals and in individuals experiencing pain or joint pathology is reviewed in the sixth section. The seventh section discusses the relationship between force appreciation and self-reported outcome measures. The final section highlights the relationship between force appreciation and physical performance tests.

2.2 Search Strategy

An initial search of the literature was performed with generic term ‘proprioception’ or ‘force sense’ from which a broader list of keywords was generated. The list included some specific terms pertaining to force sense or proprioception in joint instability. The keywords were: propriocept*, kinaesthe*, sensorimotor, muscle sense, force sens*, force appreciation, neuromuscular, force steadiness, force accuracy, force control, muscle, weight perception, muscle contraction, muscle spindles, instabil*, disloc*, sublux*, functional outcome, quality of life, perceived function. The databases searched were Medline, CINAHL, EBSCO Health Databases, Google Scholar, Medline (via Ovid), PEDro, Sports Discus, and Scopus. The literature search was enhanced by examining the reference list of articles of interest, previous review papers on proprioception and previous theses on this subject. The Google Scholar was utilised to locate articles which had cited specific research studies/author.

2.3 Dynamic stability in anterior glenohumeral joint instability

It is known that both static and dynamic “factors” and their interaction with the central neural system influences glenohumeral joint stability (Lee 2020, Myers 2002, Myers et al; 2004). The static factors include articular geometry, negative intraarticular pressure, the glenoid labrum, joint capsule, and ligaments (Myers 2004, Lee 2020, Turkel 1981).

The glenohumeral ligaments are collagen fibre bundles of varying thickness within the joint capsule (Gohlke et al., 1994; Itoigawa & Itoi, 2016).The glenohumeral joint ligaments contributing to anterior stability are superior, middle, and inferior from a cephalad to caudad orientation.

The superior glenohumeral joint ligament originates from the superior-anterior aspect of the glenoid, courses across the rotator interval and attaches to the lesser tuberosity of the humerus. The middle glenohumeral ligament originates from the anterior rim of glenoid and the labrum blends with fibres of subscapularis and attaches to the lesser tuberosity of the humeral head (Itoigawa & Itoi, 2016). Due to their slightly different orientation, they become taut at varying degrees of abduction and humeral rotation hence different stabilising roles have been identified through the range of humeral abduction and external rotation (Dodson & Cordasco, 2008; Itoigawa & Itoi, 2016; Turkel et al., 1981). In a cadaver-based study by Turkel et al. (1981) the relative contribution to stability by limitation of external rotation at various ranges of abduction was identified. It was reported that subscapularis muscles limited external rotation to a large extent at 0 ^{o} abduction, at 45 ^{o} abduction the middle glenohumeral ligament, anterosuperior fibres of inferior glenohumeral ligament, and the subscapularis muscle provided stability and at 90 ^{o} shoulder abduction the inferior glenohumeral ligament further stabilised the shoulder during external rotation (Turkel et al., 1981).

The inferior glenohumeral ligaments are described as ‘hammock’ like structure that extends from anteroinferior to posteroinferior portion of the glenoid. The anteroinferior glenohumeral ligament is an important structure contributing to anterior stability preventing anterior and inferior translation of humeral head at 90 ^{o} abduction and external rotation (Itoigawa & Itoi, 2016). The stabilising role of the superior glenohumeral ligament is not clearly identified and there is some evidence that it may function to prevent downward dislocation of the humerus when the arm is in a dependent position (Turkel et al., 1981).

The dynamic stabilisers include the rotator cuff muscles primarily subscapularis, infraspinatus, supraspinatus, teres minor but also include biceps brachii, latissimus dorsi, pectoralis major, and anterior deltoid muscles (Abboud & Soslowsky, 2002; Bassett et al., 1990). Subscapularis, infraspinatus and teres minor forms a transverse force couple and contribute to anterior-posterior stability at the glenohumeral joint (Myers et al. 2004, Werner et al; 2006, Ishikawa et al. 2023). Subscapularis is considered as the primary anterior stabiliser limiting humeral external rotation in mid-range of abduction (Turkel et al., 1981; Werner et al., 2007). In a cadaver study performed by Werner et al. (2006) shoulder joints were loaded with an anteriorly dislocating force and the tension exerted by subscapularis muscle on humeral head translation was simulated by applying 30N traction force to the muscle. It was observed that the total effect of subscapularis tension prevented anterior inferior translation of humeral head in an abducted and externally rotated position. Cadaveric shoulders have also been tested to examine the simulated effect of long head of biceps brachii contraction on glenohumeral translation (Itoi et al., 1994; Pagnani et al., 1996). When 55 N force was applied to the biceps tendon with the shoulder in a position of 45^{o} elevation and neutral rotation, the anterior humeral translation by decreased by 10.4mm (Pagnani et al., 1996).

Thus, anterior glenohumeral joint stability is maintained by combined synergy of static and dynamic stabilisers. This is mediated by the sensorimotor system which comprises of sensory, motor, and central integration and processing components. Proprioception, defined as the ability to sense joint position and movement and forces generated or applied to the joint contributes to this sensorimotor system (Myers et al., 2006; Myers & Lephart, 2000). The mechanoreceptors in capsuloligamentous structures, muscle tendons, and skin around the shoulder provide sensory input, which is integrated at spinal and central level, resulting in reflex and coordinated muscle activation, coactivation of shoulder muscles, and regulation of muscle tone and stiffness. These mechanisms occur subconsciously and are referred to as neuromuscular control at the shoulder (Myers et al., 2006; Myers & Lephart, 2000).

A traumatic anterior glenohumeral dislocation results in increased anterior translation of humeral head on the glenoid fossa (Dodson & Cordasco, 2008; Galvin et al., 2017) . This disrupts the capsuloligamentous structures such as anterior capsule, anterior-inferior, and middle glenohumeral ligaments and musculotendinous structures, including lengthening of subscapularis (Dodson & Cordasco, 2008; Galvin et al., 2017; Myers et al., 2004). Such an injury is likely to affect the sensory input from these structures thus impairing proprioception (Lephart et al; 1994), including an alteration of reflex and preparatory muscle activation at the shoulder in response to external perturbations (Myers et al; 2004, Huxel et al; 2008). Strength deficits of the rotator cuff muscles are also documented in the literature (Edouard et al., 2011; Tsai et al., 1991) . Edouard et al. (2011) showed that in subjects with recurrent anterior glenohumeral instability that internal rotator and external rotator peak torque produced was significantly lower on the involved side when compared to the uninvolved and healthy control shoulders. Strength deficits could decrease neuromuscular control at the glenohumeral joint by decreasing the rotator cuff coactivation required for the function of the transverse force couple (Abboud & Soslowsky, 2002; Ishikawa et al., 2023). Thus, the combined effect of strength deficits and decreased neuromuscular control may affect the dynamic stability at the glenohumeral joint notably.

Some authors think that in young, active individuals' surgery is the preferred option for management of recurrent anterior instability to allow safe return to sports (Donohue et al., 2016; Elsenbeck & Dickens, 2017). Surgical options include arthroscopic repair of the glenoid labrum or open repair through subscapularis split approach. The labral repair is often accompanied by inferior capsular shift to eliminate inferior capsule redundancy (Dodson & Cordasco, 2008; Meller et al., 2007). In the presence of significant glenoid defect, a Latarjet procedure is indicated where an osteotomy of the coracoid process is performed and used to bridge the glenoid defect. The subscapularis muscle is incised in this procedure and may cause deficits in rotator cuff muscle strength and endurance (Caubère et al., 2017; Edouard et al., 2013). Anterior stabilisation surgery is thought to restore proprioception by restoring the capsuloligamentous structures (Lephart et al., 1994; Pötzl et al., 2004; Zuckerman et al., 2003).

However, despite surgical tensioning of the capsuloligamentous structures glenohumeral translation with "micro-instability "at glenohumeral joint can persist even at one year after surgery (Lädermann et al., 2016). Kinematic analysis showed that anterior translation of humeral head persisted during flexion and abduction following surgery and was not significantly different from preoperative values (Lädermann et al., 2016). This agrees with Wright et al. (2015) who showed that the kinematic characteristics for abduction in scapular and coronal plane, and forward flexion remain unaltered after anterior stabilisation surgery and were significantly different from healthy individuals. The exact mechanisms for micro instability are still unknown and may be due to the incomplete restoration of proprioception, leading to decreased neuromuscular control at the glenohumeral joint (Lädermann et al., 2016).

In summary, anterior stability at the glenohumeral joint is produced by static and dynamic stabilisers and their interaction through the sensorimotor system. Traumatic anterior instability damages the articular, capsuloligamentous, and musculotendinous structures which affects not only the muscle strength but also the afferent input required for proprioception. Proprioception contributes to such sensorimotor interaction and to the dynamic stability at the glenohumeral joint and is reviewed in the next section. Anterior stabilisation surgery restores the mechanical restraints but deficits in muscle strength and endurance are noted post-surgery. Micro instability at the glenohumeral joint persists after surgery and may affect the dynamic stability of the joint.

2.4 Proprioception and force appreciation

This section begins with an explanation of proprioception, specifically force appreciation with an intention to clarify different terminologies used in defining force appreciation. A brief overview of peripheral, spinal and central structures involved in force appreciation concludes this section.

2.4.1 Proprioception and defining force appreciation

Our interaction with the environment depends on our ability to respond to signals coming from the environment and our moving body so that we can react quickly to rapidly changing circumstances. This requires knowledge about the position and movement of our body and the integration of active forces (muscular) and external forces that act upon the body. Even in the absence of vision, one has an awareness of motor output and movement outcome. This is termed 'proprioception' and includes position and movement sense, sense of effort, tension and force, and sense of balance (De Graaf et al., 2004; Proske & Gandevia, 2012; Walsh et al., 2011).

Proprioception differs from the basic sensory modalities as the sensory signals associated with it are not always associated with specific recognisable sensation. Yet the position and movements of our limbs and the muscular forces produced can be appreciated by humans with reasonable accuracy (Proske & Gandevia, 2012; Walsh et al., 2011). Proprioception is currently viewed as a construct derived from assimilation and processing of signals from visual receptors, joint, cutaneous and muscle receptors, vestibular apparatus, and corollary discharge (from motor cortex to sensory areas of the brain). This leads to awareness of movement outcome and contributes to movement control which occurs subconsciously (Poulet & Hedwig, 2007; Sperry, 1950; Wolpert et al., 1995). A lesser reviewed function is contribution of proprioception in formation of body schema and image (Proske & Gandevia, 2012).

Since the beginning of the 19th century various terminologies have been used to described proprioception. It has been described as 'kinaesthesia' or 'position sense' or both, and the research focus was on identifying the sensory receptors and the processes involved in the conscious perception of these sensations (Goodwin et al., 1972; Jones, 1972; Proske, 2005; Proske & Gandevia, 2009; Stillman, 2002). The concept of ‘kinaesthesis’ was introduced by Bastian (1880), who proposed a hybrid theory that sensations of movement and position sense could have both peripheral and central contribution. His view that motor areas of the cerebrum were kinaesthetic centres which relayed sensory information regarding the movement being executed, was later abandoned in favour of Sherrington’s theory (Jones, 1972; Proske & Gandevia, 2012; Stillman, 2002).

Sherrington (1906) argued awareness of limb position can occur even in absence of motor commands when limbs are relaxed. He proposed that sensory signals from muscles and joints contributed to awareness of body position and movement which was later described as ‘proprioception’. He classified sensory receptors into teleceptors (responding to stimuli from distant external environment), exteroceptors (responding to stimuli from immediate external environment), interoceptors (visceral) and proprioceptors which relay information about mechanical stimuli within the musculoskeletal system (Jones, 1972; Proske & Allen, 2019; Proske & Gandevia, 2012; Stillman, 2002). Further research in this area showed that proprioception includes position and movement sense, and sense of effort, heaviness and force and sense of balance (Cafarelli, 1982; Mccloskey et al., 1974; Proske & Gandevia, 2012; Roland & Ladegaard-Pedersen,1977).

In later years research focus shifted to investigation of sense of effort, force and heaviness (Mccloskey et al., 1974). Early experiments investigating sense of force examined the ability to match tension or estimate the weight lifted, or ability to maintain desired level of submaximal force or to discriminate between differing levels of forces (Cafarelli, 1982; Jones, 1986; Jones & Hunter, 1983; Mccloskey et al., 1974; Roland & Ladegaard-Pedersen, 1977). The observations from these various studies demonstrated that force appreciation occurred by means of perception of muscle effort or heaviness. Hence sensation of force was considered synonymous to sense of effort or heaviness (Cafarelli, 1982; Mccloskey et al., 1974; Proske, 2005).

McCloskey et al. (1974) were first to profess that sense of tension can be revealed if subjects were specifically instructed to match the forces and not the effort in the reference arm. Their observations were supported by Roland & Ladegaard-Pedersen, (1977) who suggested that sensation of force/tension was different from sense of effort and heaviness. In subsequent years, it was debated whether sensation of force was peripheral or central in origin (Cafarelli, 1982; Gandevia et al., 1980; Gandevia & Kilbreath, 1990; Gandevia & McCloskey, 1977; Monjo et al., 2018; Proske & Allen, 2019; Walsh et al., 2011). Some studies showed evidence of contribution of peripheral afferents to our sense of force (Cafarelli, 1982; Mccloskey et al., 1974; Proske & Allen, 2019) and others thought that it is central in origin (De Graaf et al., 2004; Jones & Hunter, 1983; Taylor et al., 2000). A more pragmatic view is that both peripheral and centrally generated signals contribute to sense of force but it is difficult to quantify their individual contribution (Luu et al., 2011; Proske & Allen, 2019).

Force appreciation is not clearly defined in literature and this stems from the differences in the methods used to investigate this modality leading to the use of different terminology used in publications. To minimise confusion, in this thesis the term 'force sense' refers to the afferent processes initiated by muscle contraction, and 'force perception' is used to describe the central transformation of these sensory signals (Proske & Allen, 2019). Force acuity involves how accurately individuals perceive a produced force to match with their muscle's actual force output. The term 'force appreciation' describes the entire proprioceptive system involved in encoding and processing the magnitude of voluntary muscle output (Brereton, 2007). The focus of this thesis will be on understanding force appreciation in subjects with anterior stabilisation surgery by investigating force acuity.

2.4.2 Peripheral mechanoreceptors and spinal pathways in force appreciation

The mechanoreceptors contributing to force appreciation are muscle spindles, Golgi tendon organs, capsuloligamentous receptors (Ruffini, Pacini, Golgi-Mazzoni), cutaneous (Merkel cell, Pacinian and Meissnner corpuscles) and intramuscular pain receptors (Macefield, 2005; Nyland et al., 1998; Stillman, 2002). The sensory information from these receptors is conveyed to the brain via various afferent pathways. The key receptors involved in encoding of force signals are muscle spindles, Golgi tendon organs and cutaneous receptors (Proske & Allen, 2019; Roland & Ladegaard-Pedersen, 1977). However, it can be argued that joint receptors could also provide useful information when exposed to adequate tensile forces through capsuloligamentous structures (Macefield, 2005). Further detail concerning these receptors and central pathways is presented below.

2.4.2.1 Muscle receptors

The Golgi tendon organ

Golgi tendon organs are tension sensitive mechanoreceptors located at the muscle-tendon or muscle-aponeurosis junction (Jami, 1992; Mileusnic & Loeb, 2006; Moore, 1984). Despite their name, they are mostly located in series within the muscle fibres (Jami, 1992; Mileusnic & Loeb, 2006). Nevertheless, the mechanical properties and characteristics of tendon organs is extensively researched in animal tendons. Due to their location being in series with the muscle fibres, the Golgi tendon organs are sensitive to forces developed by stretch or muscle contraction/activation. A single tendon organ receives input from different 10-20 motor units with different combinations of muscle fibres (e.g., slow oxidative, fast oxidative glycolytic/fatigue resistant) (Moore, 1984).

Golgi tendon organs are most sensitive to active muscle contractions with a mean threshold activation at forces as low as 1.33 N (Proske & Gandevia, 2012).They primarily display dynamic sensitivity to changes in force primarily (Jami, 1992; Mileusnic & Loeb, 2006). It is suggested that tendon organs' activity do not indicate absolute force levels, but work as a detector of small variations in force level (Jami, 1992).

The dynamic sensitivity of tendon organs is greater when a contracting muscle is lengthened versus being shortened (Crago et al., 1982). However, the sensitivity of tendon response is not affected by increase in velocity of muscle stretch (Crago et al., 1982; Jami, 1992; Mileusnic & Loeb, 2009). While it is also understood that a single tendon organ's discharge rate only reflects the number of motor units firing, it is plausible that the summed responses of discharge rates of all the tendon organs in a muscle could provide an estimate of total muscle force (Crago et al., 1982; Gregory & Proske, 1979; Mileusnic & Loeb, 2009).

The afferent signals from the Golgi tendon organs are conveyed by fast conduction group 1b fibres to the spinal cord (Jami, 1992; Macefield, 2005). These fibres act on alpha motor neurons either disynaptically or polysynaptically via 1b inhibitory interneurons in laminae V and VI. This synaptic pathway produces autogenic inhibition of agonist and synergist muscles and excitation of antagonist muscles. It is understood that this reflex mechanism contributes to a "protective function" against excessive tension developed in a muscle or when a joint reaches its physiological limit of range (Brink et al., 1983; Jami, 1992; Moore, 1984). This inhibitory effect of homonymous muscles by 1b inhibitory interneurons is regulated by excitatory or inhibitory inputs from the from supraspinal centres so that appropriate force/tension could be generated during a given task (Jami, 1992;).

Muscle spindles

There is notable evidence regarding the role of muscle spindles in force appreciation (Brooks et al., 2013; Luu et al., 2011; Monjo & Forestier, 2018). Muscle spindles are stretch-sensitive mechanoreceptors situated in parallel to extrafusal muscle fibres. The density of muscle spindles is highest in muscles involved in dextrous tasks (e.g., intrinsic muscles of the hand) or in maintaining position of body and balance (cervical muscles) (Macefield & Knellwolf, 2018). The spindle consists of bag 1, bag 2 and chain fibres. The bag 2 and chain fibres are innervated by type 2 afferents and γ-static axons and whereas the bag 1 are innervated by type 1 afferents and γ-dynamic axons (Macefield & Knellwolf, 2018; Proske, 1997).

Muscle spindles encode changes in muscle length during active contractions and passive conditions (Burke et al., 1978; Vallbo, 1971). This function is attributed to the dynamic sensitivity of bag 1 fibres to change in muscle length and velocity of muscle stretch. The bag 2 and chain fibres are considered as one functional unit and they maintain static sensitivity of the muscle spindle when the muscle is held at constant length or during an unloading (shortening) muscle contraction (Macefield & Knellwolf, 2018).

Spindle discharge rate increases linearly with increases in joint angle velocity (Jones et al., 2001). During active muscle contraction, the spindles are more effective at encoding muscle length changes due to generated tension rather than angular position(Macefield & Knellwolf, 2018). Blum et.al (2017) suggested that muscle spindles can also encode force developed within a muscle when it is passively stretched. Through computational modelling, they showed that the initial firing rate in cat gastroc-soleus muscle spindle when exposed to a passive stretch at different velocities corresponded to changes in rate of rise in force (df/dt) as well as acceleration. The authors (Blum et al., 2017) concluded that the initial rise in force (df/dt) at the onset of lengthening reflected short range stiffness due to actin-myosin crossbridge formation.

In muscle spindles, an intrafusal fibres contraction accompanies extrafusal muscle contraction. During isometric contractions, the initial spindle discharge rate is higher at the onset of muscle contraction and then decreases as the muscle shortens further (Horcholle-Bossavit et al., 1988; Macefield & Knellwolf, 2018). However, the γ-static activation is sufficient to enhance the background activity of the spindles and increase their static response to stretch, ensuring that spindle discharge does not cease its role with muscle shortening (Burke et al., 1978; Macefield & Knellwolf, 2018). Spindle responses are greater during lengthening contractions, and with changes in load or speed of contraction (Burke et al., 1978; Macefield & Knellwolf, 2018; Proske, 1997; Vallbo, 1971).

2.4.2.2 Joint receptors and other intramuscular receptors

Small diameter free nerve endings (group III and IV) located in muscle bellies, tendons and connective tissue sheath are responsive to moderate painful or non-painful muscle stretch, pressure, or contractions (Gandevia, 1998; Kaufman et al., 2022; Macefield, 2005; Mense, 1993). The firing rate of these afferent fibres increases with sustained contraction for several minutes suggesting that their activity is increased by muscle ischaemia and introduction of metabolites such as potassium, lactate and bradykinin into the muscle. The combined activation of both group III and IV muscle afferents can alter motoneuronal output at the spinal level during fatiguing contractions and thereby decrease muscle force (Gandevia, 1998; Taylor et al., 2000).

2.4.2.3 Cutaneous receptors

Afferent endings from receptors such as Messner and Pacinian corpuscles, Merkel cells and Ruffini endings respond to touch, pressure, stretch stimuli applied to the skin. Altering cutaneous input impairs force matching and weight perception in tasks which involve gripping or lifting weights with hand (Gandevia et al., 1980; Gandevia & McCloskey, 1977; Jones & Piateski, 2006). Whilst not directly involved in signalling muscle force, it is suggested that the slow adapting receptors (Merkel and Ruffini ending) signal the spatial distribution of force on the skin that may occur with skin indentation in grasping tasks involving the hand. This information is used by the nervous system to form an internal model which contributes to pre-programming of gripping and lifting forces (Jones & Piateski, 2006; Macefield, 2005; Monzee et al; 2002; Johansson et al., 1987).

2.4.3 Spinal pathways for force sensation

The afferent input from the various receptors signalling force sense travel along multiple spinal pathways making connections with subcortical structures before terminating in cortical regions. The spinal pathways identified include spinocerebellar tract, spinothalamic tract and posterior column-medial lemniscal pathway (Bosco & Poppele, 2001; Gilman, 2002; Proske & Gandevia, 2012; Stillman, 2002).

The spinocerebellar tract conveys subconscious information from musculotendinous (the Golgi tendon organs, muscle spindles) and cutaneous receptors (pressure and touch receptors) to the cerebellum via thalamus. The spinocerebellar tract system comprises of dorsal and ventral spinocerebellar tract (lower trunk and lower limbs) and cuneocerebellar and rostral cerebellar tract (upper trunk and upper limbs). Understanding of the role of spinocerebellar tract in force appreciation is derived from research studies using microelectrode technology to record activity of dorsal spinal cerebellar tract (DSCT) neurons in decerebrate cats. The dorsal spinocerebellar tract also gives collaterals to nucleus Z in the medulla which then further projects to thalamus and cortex (Bosco & Poppele, 2001; Gilman, 2002; McIntyre et al., 1984; Proske & Gandevia, 2012; Stillman, 2002).

In the context of isometric force matching, when the matching force is a self-generated task, signals generated by activation of the Golgi tendon organs and the fusimotor activity from muscle spindles constitute the ‘reafferent signal’. This information is conveyed via the DSCT to the cerebellum where comparison occurs between the ‘reafferent signal’ and the predicted afferent signal ‘efference copy’ generated by the motor command. The ‘efference copy’ is based on past experiences. If there is a sensory discrepancy, then an inhibitory signal is generated to attenuate the ‘reafferent signal’ relayed by the DSCT. Consequently, the sensory feedback generated by our own actions is perceived with less importance than the ‘exafferent signal’ (difference signal) (McIntyre et al., 1984; Proske & Gandevia, 2012; Walsh et al., 2011). This is a simplified explanation of the mechanisms contributing to force perception when the matching force is self-generated, which is particularly relevant to the current study. It is thought that the reafferent signals are attenuated by a constant gradient which is independent of the force level, hence there is always some reafferent feedback available for proprioception (Walsh et al., 2011).

Sensory information related to conscious awareness of pressure, vibration, two-point discrimination, touch and proprioception is also carried via the posterior-column-medial lemniscal pathway to the sensorimotor cortex. This includes input from group III afferents which respond to muscle stretch and/or contraction during initiation of submaximal muscle activation with further increases in discharge with conditions such as muscle fatigue (Taylor et al., 2000). This spinal pathway could qualify as an alternative route of relaying force sense to supraspinal centres (Gilman, 2002). This tract ascends through the spinal cord via the fasciculus cuneatus (above T6) and the fasciculus gracilis (below T6) to synapse with nucleus cuneatus and nucleus gracilis in the medulla. The secondary projection from the medulla crosses the midline to enter the medial lemniscus, which ascends to ventral posterolateral nucleus of thalamus and then to the primary sensorimotor cortex (Gilman, 2002; Stillman, 2002). Although the spinothalamic tract is the primary pathway for perception of pain and temperature it also receives information from group III & IV afferents from intramuscular mechanoreceptors. Its activity is increased with fatiguing muscle contractions and signals muscle pain. Regarding this point, perhaps group III and IV afferents do not directly signal muscle force, but likely modulate motor unit firing rates and thus decrease the force during prolonged muscle contractions (Gandevia,1998; Gilman, 2002; Taylor et al., 2000).

2.4.4 Central processing of force appreciation

The supraspinal areas involved in movement control include cerebral cortex, basal ganglia, cerebellum, and thalamus. From an engineering perspective, one can imagine these sites to be interconnected processors and sub-controllers within our CNS (Jones, 2014).

Studying the cortical neuronal activity involved in the coding of force has been of interest since the pioneering research by Evarts (1968,1969). Our understanding of force encoding in the cortical areas is derived from observation of cortical neuronal activity in primates performing a behavioural task that involves generating an isometric force in different directions or goal-directed reaching (Boline & Ashe, 2005; Georgepoulos et al; 1992., Riehle et al., 1994; Sergio et al., 2005). Findings from these studies showed that the initial neuronal activity begins with a strong tonic discharge before force onset (Sergio et al., 2005). Such studies also showed that the neuronal activity (phasic and tonic discharge) in the motor cortex M1 is primarily concerned with direction and change in force output rather than the magnitude of the force generated (Georgepoulos et al. 1992).

Studies show that only a small percentage of neurons in M1 encode magnitude of force (Boline & Ashe, 2005; Kalaska, 2009; Sergio et al., 2005; Taira et al., 1996). Increases in the magnitude of force are accompanied by an increased firing rate of recruited cells rather than recruitment of additional cells (Ashe 1997).

More recently, the role of various cortical areas in coding of force output during an isometric gripping task in humans was investigated using neuroimaging techniques (De Graaf et al., 2004; Keisker et al., 2010; Kim et al., 2023; Spraker et al., 2007). Contrary to the previous research in primates, DeGraaf et al., 2004 showed the awareness of force in humans during movement execution involves not only primary motor areas but other brain structures, particularly the posterior insula, primary sensorimotor area and associated somatosensory areas. Further research by Spraker et al. (2007) using fMRI showed activation of contralateral and ipsilateral M1, globus pallidum and striate nucleus in basal ganglia, and the thalamus in encoding of force amplitude and rate of change of force. The putamen and caudate nucleus in basal ganglia were concerned with coding the duration of force. Similarly, studies which investigated blood-flow changes in sensorimotor cortex reported activation of ipsiliateral cerebellum along with contralateral M1 during generation of submaximal grip force (Keisker et al; 2010; Dettmers et al., 1995). Another study (Yoon et al., 2014) using fMRI during an isometric force control task at the ankle showed activation intensity increased in the cortical and subcortical regions with an increase in force levels from 10% to 70% MVC, but the activation volume remained unchanged. This showed that as the magnitude of target force increased force matching occurred with rate coding rather than increased recruitment of cortical neurons. The study by Yoon et al. (2014) also highlighted that areas activated in parietal and occipital cortex were concerned with visual processing during isometric force tracking. The activation in these areas did not scale linearly with increased magnitude of target force level.

In summary, the force appreciation process can be conceptualised to involve both feedforward and feedback processes as described by Franklin & Wolpert, (2011). Theoretically the intention to generate a matching force creates an action plan from the cortical and subcortical centres involved in force generation. This is simultaneously compared with the input (force encoded) from the peripheral receptors by a difference calculator. Force perception occurs when there is sensory discrepancy. In an isometric force control task similar to one used in the current study, it is likely that there is a constant shift between the feedforward and feedback control processes where different cortical and subcortical regions are involved for accurate force matching.

2.5 Force appreciation measurement

This section describes various approaches to measure force appreciation in humans. This includes a brief overview of methods such as discrimination of stimuli (weight or force) or scaling where the magnitude of stimuli (force or weight) is estimated or produced. A description of force matching and force control tasks relevant to assessment of force appreciation in our study concludes this section.

The study of force or weight perception is derived from psychophysics which is focused on examining the association between physical stimuli and perception of those stimuli (Jones, 2003; Jones & Tan, 2013). Various attributes of a physical stimuli, such as intensity, quality, extension and duration have been studied. In psychophysical research, two broad areas are identified each involving a different set of experimental procedures. The first type of research is focused on measurement of sensory thresholds (detection) and the second area is focused on examining the sensory attributes such as the ability to differentiate or identify stimuli and perceive its intensity (identification, discrimination and scaling) (Coren, 2003; Jones & Tan, 2013).

Measurement of sensory threshold can be determined by use of absolute threshold or difference threshold in experimentation. Absolute threshold is defined as smallest amount of stimulus required to produce a sensation (Jones & Tan, 2013). In this method, the stimulus is applied under passive conditions which contrasts with studying force appreciation involving active generation of muscle force.

A difference threshold is defined as the amount of change in stimuli required to produce a just noticeable difference in sensation (JND) (Jones & Tan, 2013). Weber's law that was conceived by a German physiologist E.H. Weber (1838) states that change in stimulus intensity ($\Delta\Phi$) that can be discriminated is a constant fraction (c) of the stimulus intensity (Φ).

$$\Delta\Phi/\Phi = c$$

Weber's constant has been shown to be valid for a wide range of stimuli including force and weight sensation (Jones, 2003; Jones & Tan, 2013; Warren, 1981). Whilst Weber's fraction indicated that there is a factorial relationship between perceived force and reference force, other research (Cafarelli & Bigland-Ritchie, 1979; Cain & Stevens, 1971; Jones & Hunter, 1983) suggests that there should be a logarithmic relationship between the stimulus intensity and perceived intensity of stimulus. In the context of force appreciation, a non-linear relationship between reference and perceived force was observed under conditions of fatigue, and with muscle-length changes (Cafarelli &

Bigland-Ritchie, 1979; Jones & Hunter, 1983; Proske et al., 2004; Weerakkody et al., 2003).

Some recent studies have used Borg's scale or a visual analog scale to estimate perceived force (Lauzière et al., 2012; McGorry et al., 2010; Troiano et al., 2008). Whilst estimation of force using a subjective scale has clinical applications, it can be argued that unless subjects are instructed clearly, they could be estimating the effort of contraction rather than the actual tension/force produced (Mccloskey et al., 1974; Roland & Ladegaard-Pedersen, 1977).

Another method used in force appreciation research is the magnitude production method where the numerical estimate of the reference force is provided, and the subject is required to match that force with the comparison limb either with visual feedback or without feedback (Jones & Tan, 2013; Jones 1989; Williams et al., 1992; Walsh et al., 2011; Adamo et al., 2012; Weerakody et al., 2003;). In a contralateral force matching task, the isometric forces exerted by muscles in one limb (reference limb) are matched by homologous or non-homologous muscles in the comparison limb (McCloskey et al., 1974; Jones & Hunter 1989; Walsh et al., 2011; Adamo et al 2012; Park et al., 2008; Monjo et al., 2018). In an ipsilateral force matching task, the reference and comparison forces are produced by corresponding muscle group on the same side (Adamo et al., 2012; Espindola et al., 2011; Onneweer et al., 2016; Park et al., 2008; Walsh et al., 2011). In some instances, sequential force matching task takes place without visual feedback and require reliance on memory-based internal representation of the reference force (Adamo et al., 2012). In such protocols the subjects attain the target force with their reference limb with visual feedback and then a comparison matching force is generated without visual feedback (Adamo et al., 2012; Walsh et al., 2011;).

Isometric force control tasks are also used in force appreciation studies and require subjects to match the target force signal with visual feedback as closely as possible for approximately 10-20 seconds (Bandholm, et al., 2008; Komar et al., 2016; Slifkin & Newell, 1999; Williams et al., 1992). Such an experimental protocol involves force matching and force modulation and could allow a more comprehensive examination of the processes involved in force appreciation. This may be especially relevant in presence of injury, pain, or neuromuscular disorders (Bandholm et al., 2006; Bandholm, et al., 2008; Floegel et al., 2022; Lodha et al., 2010; Ward et al., 2019) or where comparison between affected and unaffected limb is the focus of the research study (e.g., shoulder injury).

Accuracy and precision in force matching are the measures used in an isometric force control task (Magni et al., 2021; Williams et al., 1992). Accuracy is defined as the difference between the comparison force and the target force. It is also termed bias or error and the terms constant/absolute error, relative error and percentage error are used to describe the difference between the comparison and the target force levels (Espindola et al., 2011; Jackson & Dishman, 2000; Jones, 2003; A. Kumar et al., 2017; Maenhout et al., 2012). In a force matching task if a subject produces 90g force to match a target level of 100g, the accuracy is described as 90%, the percentage error is 10%, the absolute error equals 10g and the relative error equals 0.10 (Brereton, 2007). In an isometric force control task, the root mean square error (RMS error) is appropriate to measure force accuracy and is calculated by subtracting the target force from the force generated by the participants (Magni et al., 2021; Rice et al., 2021; Slifkin & Newell, 1999). It is thought that force accuracy provides information about how the central nervous system assimilates sensory information from various receptors and the internal model to predict the final force output (Onneweer et al., 2016; Proske & Gandevia, 2012).

Precision is established with measures that focus upon variability in the subject's force signal. Thus, it demonstrates the range of variability while maintaining a constant level of force and can be regarded as "steadiness" (Gandevia & Kilbreath, 1990; Jones, 2003; Kumar et al., 2017). The precision is often determined by calculating the standard deviation (SD) of the force signal or coefficient of variation which quantifies the dispersion of force produced from the signal average (Magni et al., 2021; Williams et al., 1992). Precision of force control is influenced by activation of cortical and subcortical regions, and their subsequent influence on motor units via descending tracts and the characteristics of individual motor units (Enoka & Farina, 2021; Yoon et al., 2014). Both accuracy and precision/steadiness provide a measure of successful performance of an isometric force control task. It can be argued that these measures are not interchangeable and should be distinguished in the context of force appreciation experiments (Kumar et al., 2017).

The complexity of the force control task can be increased in various ways. In some protocols the difficulty of the task is increased by requiring subjects to perform dynamic force matching. This could involve participants tracking a sinusoidal waveform (Perraton et al., 2013, 2017; Ward et al., 2019). Additionally, it may require subjects to regulate their force across agonist/antagonistic muscle groups (Rice et al., 2021). Changing the amount of visual feedback (visual gain) or removal of visual feedback during force matching also increases the difficulty of force control task (Baweja et al., 2009; Hou et al., 2008; Noble et al., 2013; Sarlegna et al., 2010; Tracy, 2007; Tracy et al., 2007; Vaillancourt et al., 2003). Some studies reported that force accuracy in an isometric force control task decreased in the absence of visual feedback. This was related to activation of different brain regions depending on presence or absence of visual feedback (Limonta et al., 2015; Noble et al., 2013; Shafer et al., 2019; Vaillancourt et al., 2003). Further complexity might be implemented with dual tasks where the forces applied may require modulation in magnitude as well as direction. For example, using a video game interface where subjects must reach targets as fast as possible while exerting submaximal forces in different directions (Yen et al., 2019).

Another less explored means of increasing the task complexity include force matching under ballistic conditions where subjects are required to attain a submaximal target force level as fast as possible and hold that force for a certain time level (Kumar et al., 2017; Miyamoto et al., 2020). As might be expected, such a task is more challenging and results show that overall, the accuracy and precision is lower when the task requires a greater rate of force development (Miyamoto et al., 2020). It could be argued that this scenario/condition is more relevant in many physical tasks. For instance, where a person playing sport must be able to generate forces fast and accurately to perform the tasks successfully or perhaps to avoid injury.

In summary, force appreciation can be investigated with various experimental methods. The ipsilateral isometric force matching method is useful to allow comparison between the affected and unaffected limbs. The isometric force control method requires force matching and force modulation, hence can provide more comprehensive understanding of the processes involved in force appreciation. Increasing the task complexity by requiring subjects to attain the target force quickly in the presence of visual feedback will add novelty to experimental method. Force accuracy and force steadiness are two distinct measures and examining both will be more appropriate for the isometric force control task undertaken in the current study.

2.6 Force appreciation research in peripheral joints

This section starts with a brief overview of research on force appreciation in individuals without pathology, with a focus upon force matching or tracking with isometric activation. It also includes review of research on force appreciation at the shoulder joint and other peripheral joints after ligament injuries, particularly those studies involving a post-surgical population.

2.6.1 Force appreciation at different force levels in individuals without pathology

Examination of force appreciation at different force levels was explored by several studies using isometric force matching /tracking methods (Bandholm et al., 2006; Bandholm, Rasmussen, et al., 2008; Espindola et al., 2011; Jones & Hunter, 1983; Li, et al., 2020; Onneweer et al., 2016; Salonikidis et al., 2009; Walsh et al., 2011; Yoon et al., 2014).

In two such studies the focus was to examine the perceptual relationship between the target force and the reproduced force output (Jones & Hunter, 1983; Walsh et al., 2011). In a pioneering research study Jones & Hunter, (1983) used a contralateral isometric force matching method for elbow flexors where the reference force of one limb was matched with force reproduced by the contralateral limb. The target forces ranged from 15% to 85% MVC and the results showed that maximum force accuracy was obtained at mid-range force level (50% MVC). The target forces at 15% and 25% MVC were overestimated. They concluded that forces are matched relative to the reference force level (Jones & Hunter, 1983).

In another study, Walsh et al. (2011) investigated whether the perceptual relationship between the target (reference) and reproduced force at the index finger differed if the target was applied externally or self-generated by the muscles. The results showed that a target force of 15% MVC was overestimated, accurate matching occurred at 35% MVC and higher forces at 55% and 75% MVC were underestimated (Walsh et al., 2011). The exact mechanisms for the directionality in force matching error were unclear. Similar results were obtained by Li et al. (2020) (Li, et al., 2020) examining the effect of different force levels on isometric pinch force perception, where both the target force and reproduced force were self-generated by muscle action.

Two other studies (Espindola et al., 2011; Onneweer et al., 2016) used a similar isometric force matching protocol, where the target force was achieved with visual feedback and force reproduction occurred without visual feedback. Espindola et al. (2011) showed that for isometric force matching at the knee, force accuracy was decreased at target force of 30% & 50% MVC in comparison to 70% MVC. Contrasting results were obtained in the study by Onneweer et al. (2016) where maximum force accuracy (decreased errors) was at mid-range force levels. An overestimation of low-level target forces and underestimation of high target forces conforms with the results other studies (Jones & Hunter, 1983; Li et al., 2020; Walsh et al., 2011). It could be that at higher forces more motor units are recruited, thereby increased number of Golgi tendon organs are encoding the force, and hence lesser errors in force matching.

Whilst these above mentioned studies (Espindola et al., 2011; Jones & Hunter, 1983; Li et al., 2020; Onneweer et al., 2016; Walsh et al., 2011) examined force appreciation with isometric force reproduction protocol in absence of visual feedback, other studies (Bandholm et al., 2006; Bandholm, et al., 2008; Noble et al., 2013; Salonikidis et al., 2009; Yoon et al., 2014) investigated the effect of different force levels using an isometric force tracking protocol. In one such study (Salonikidis et al., 2009) force steadiness was examined during isometric wrist flexion with a force tracking protocol. It was found that force steadiness increased as the target force level increased from 10% to 75% MVC. Salonikidis et al. (2009) proposed that decreased steadiness at lower target force was related to synchronization of motor units. Bandholm and colleagues (2006, 2008) results showed contrasting findings wherein the force steadiness for shoulder abduction during isometric force tracking was poorer with increase in target force levels from 20% to 35% albeit only in a submaximal force range. In another study (Yoon et al., 2014) isometric force tracking for ankle dorsiflexors was examined at target forces ranging from 10% to 70% MVC. A fMRI was also performed to study the brain activation during the force control task. The results showed that force steadiness was lesser with increase in force levels. It was found that with increase in target force levels the activation in cortical and subcortical areas increased. The authors (Yoon et al., 2014) thought that increased activation of other brain regions indicated that force control had become more challenging with increases in target force level during the task. Similarly, the results from a study by Noble et al. (2013) showed that during isometric grip force matching task at target forces 35% and 70% MVC, the force accuracy was greater at 35% MVC than at 70% MVC.

In summary, perception of force at different target intensities varies as a function of the relative magnitude of the reference force level with a tendency to overestimate low forces and underestimate high forces. The results concerning the target force where maximum force accuracy was obtained differed across studies. The results from isometric force reproduction studies showed that force accuracy was poor at submaximal target forces and perhaps testing at this level may reveal deficits in force appreciation in individuals with joint injuries. Contrasting results were reported in other studies using isometric force control task where force steadiness and accuracy was lower at higher target force levels. This indicated that an isometric force control task at 50% -70% MVC may be more challenging but also representative of the forces occurring at the shoulder in contact or collision sports. However, isometric force control task at 50%-70%MVC target force may induce fatigue of the shoulder musculature. Combining the results across studies for force accuracy and steadiness, it seems logical to use a mid to lower range submaximal target force level with an isometric activation involving tracking.

2.6.2 Force appreciation at different joint angles and muscle length

Change in joint angle changes the “geometric leverage” of the muscle-bone system as well as the length-tension relationship of the muscle. This can have an impact on the muscle torque produced and force generating capacity (Cafarelli & Bigland-Ritchie, 1979; Weerakkody et al., 2003). This concept was examined by several studies (Cafarelli & Bigland-Ritchie, 1979; Dover & Powers, 2003; Li, et al., 2020; Phillips & Karduna, 2018; Trousset et al., 2018; Weerakkody et al., 2003). Early work by Cafarelli & Bigland-Ritchie, (1979) examined the effect of change in muscle length on force appreciation using a bilateral force matching task, where activation in one muscle group was matched simultaneously by the contralateral muscle group. At the elbow joint, the length of biceps and triceps in the reference limb was altered by changing the elbow flexion and extension angle. When the reference muscle length was shortened, there was a corresponding match with 30% greater force by the indicator limb. In contrast, when biceps or triceps were tested in a lengthened position the reference force was matched with 30% lower force by the indicator limb. However, the exact joint angles at which the force matching was performed was not reported.

In a later study Werrakody et al. (2003) albeit with a small sample size (n=8) assessed a force matching task for elbow flexors at 5% and 20% MVC target torques with the reference arm in various degrees of elbow flexion (30^{o}, 60^{o}, 90^{o}, 110^{o}, 120^{o}). The indicator arm always remained at 90^{o} degree of elbow flexion. The results showed that when the angle of reference arm was greater or less than the muscle’s optimum length for peak torque generation, the indicator arm always overestimated the target torque. The errors in force matching were significantly greater at 30^{o} and 120^{o} elbow flexion. Additionally, increased EMG signals from biceps muscle were recorded with changes in joint angle indicating that target force matching at shortened and lengthened muscle lengths required greater activation. The authors concluded that centrally generated efferent output contributed to the perception of force.

Krishnan et al. (2011) also examined muscle activation with EMG on quadriceps muscle force steadiness. Isometric force matching was performed at 30^{o} and 90^{o} knee flexion angles and target forces ranged from 2%-50% at each knee angle. The results showed poor force steadiness at a longer muscle length (90^{o} deg) in comparison to 30^{o} flexion across all target force levels. Quadriceps and hamstring muscle activation was noted to be increased at 90^{o} knee flexion and this might have played a role in the observed difference.

Another study that found better force accuracy at a joint angle other than mid-range utilised a unilateral grip force matching task with the wrist in neutral, full flexion, extension, radial and ulnar deviation. Li et al. (2020) assessed target torques (10-50% MVC) at each wrist position. The results showed improved performance with decreased absolute error for full flexion than for neutral position. Notably, the maximum grip force was significantly greater in a neutral position than in full flexion. The authors concluded that when performing grip force matching in full flexion subjects may have been guided by sensations of discomfort resulting in decreased errors.

Two studies examined force accuracy at different joint angles at the shoulder joint (Dover & Powers, 2003; Trousset et al., 2018). Dover & Powers, (2003) examined the force accuracy for shoulder internal rotators at maximum range of internal and external rotation with shoulder in 90^{o} abduction with a target force of 50% MVC at each target angle. There was no significant difference in the absolute error for force reproduction between the two joint angles. This was despite the shoulder internal rotators being in either a very lengthened or shortened position. These researchers did not identify the angle at which peak torque was generated. Trousset et al. (2018) examined force accuracy at shoulder joint at various angles of arm elevation and at various target loads in the scapular plane. The results showed that normalised RMS error and normalised constant error was not significantly different between 50^{o} and 90^{o} of abduction. In this study (Trousset et al., 2018) the subjects applied a force to an external load cell attached to the wrist in a standing position. The trunk and hip were not stabilised, and it is likely that increased activation of scapular muscles could have contributed to the reproduced force at different joint angles.

In conclusion, force accuracy can be affected by changes in joint angle which produces a change in muscle length. Increased errors in force matching occur as muscle lengths diverge from an optimal point, though where that point is remains unclear. There are contrasting findings across different joints and results may reflect the numerous muscles that might span these joints having quite different muscle lengths at specific joint angles. Additionally, there is some evidence that muscle activation may affect force appreciation levels, although again it is unclear whether agonist or a combination of agonist and antagonist activity are moderators. For the shoulder joint, there was no effect with changing joint angle on internal rotator force accuracy. These muscles are important in stabilising the joint, particularly in a joint position where it is most susceptible to dislocation/redislocation. Hence, it seems logical to test force accuracy and precision at end range external rotation with the upper arm in 90^{o} degrees of abduction.

2.6.3 Force appreciation in different types of muscle contraction

Most studies have examined force appreciation with an isometric muscle activation protocol (Benze et al., 2009; Docherty & Arnold, 2008; Maenhout et al., 2012; Rice et al., 2021; Saccol et al., 2014; Sousa et al., 2017; Zanca et al., 2013). At the knee, two studies (Hortobágyi et al., 2004; Rice et al., 2015) have examined the force accuracy and force steadiness with low target forces for isometric, concentric and eccentric knee extension. In both studies, RMS error was found to be higher during eccentric activation and least with isometric activation. Similarly, steadiness of force control was decreased during eccentric muscle contraction compared with concentric contractions (Hortobágyi et al., 2004).

Concerning the shoulder joint, for force steadiness during shoulder abduction at low-medium target force levels (20-35% MVC), results from studies (Bandholm et al., 2006; Bandholm, et al., 2008) show decreased steadiness for both concentric and eccentric contractions compared to isometric contractions with increasing target force levels.

In conclusion, force accuracy and steadiness performance are increased during isometric contractions in comparison to eccentric and concentric contractions. Concerning the shoulder joint, the mechanism related to dislocation involves eccentric internal rotator activation that is acting to prevent abnormal/excessive movement into external rotation with the arm in an abducted position. To replicate this activity during a dynamic force matching/tracking task was thought to put the joint at too much risk of an injury to repaired tissues. However it was thought that an isometric task with the joint static, but at a position that replicated that which would occur close to the point of dislocation would be achievable.

2.6.4 Force appreciation at the shoulder joint

In this section we firstly review force appreciation papers associated with subjects without pathology, drawing upon some papers that were already featured in earlier sections. Thereafter, the focus is upon the effects of pathology at the shoulder joint.

In uninjured shoulders, force appreciation was examined with isometric force matching protocol at various target force levels (Bandholm et al., 2006; Bandholm, et al., 2008; Phillips & Karduna, 2018; Trousset et al., 2018), and at different joint angles (Dover & Powers, 2003; Trousset et al., 2018). The effect of different target force levels was examined only for shoulder abductors muscle group. Bandholm and colleagues in two different studies (2006, 2008) showed that force steadiness was lesser (higher SD) with an increase in target force levels from 20% MVC to 35% MVC. A similar effect of target force level was observed during concentric and eccentric contractions from 30^{o} - 120^{o} abduction (Bandholm et al., 2006; Bandholm, et al., 2008).

Another research group (Phillips & Karduna, 2018; Trousset et al., 2018) used a similar protocol in two different studies. An ipsilateral force reproduction protocol was used for shoulder abduction at three different target loads (120%, 150%, 170% of baseline torque) at three different abduction joint angles (50^{o}, 70^{o}, 90^{o}). The results of one study (Trousset et al., 2018) (n = 12) showed that the target load and joint angle did not affect the force accuracy for abductors (normalised RMS). Conflicting results were reported in the other study (Phillips & Karduna, 2018) (n= 18) where the force accuracy improved with an increase in target load at 50^{o} and 70^{o} abduction but not at 90^{o} abduction. In the second study (Phillips & Karduna, 2018) joint position sense was also examined at the same target angles with external weight at the wrist which corresponded to the target loads used in the force reproduction protocol. The order of force and joint reproduction protocol was randomised so it is unlikely that this could have influenced the results in this latter study (Phillips & Karduna, 2018). Perhaps a small sample size of the study by Trousset et al. (2018) could have contributed to different results obtained irrespective of using the same protocol as that included by Phillips & Karduna, (2018).

The internal rotators force matching accuracy at two different angles was examined by (Dover & Powers, 2003). The reliability (ICC ranging from 0.97- 0.98) for isometric force matching of shoulder internal rotators at maximum internal and external rotation at 90^{o} abduction was established in this research. Results showed that there was no significant difference in force accuracy for internal rotators at the two different angles (90^{o} internal rotation and 90^{o} external rotation).

In another study by Maenhout et al. (2012), force appreciation was investigated in a healthy control group and those with rotator cuff tendinopathy for internal and external rotators at a target force of 50% MVC. The shoulder was positioned in 45^{o} abduction with 90^{o} of external rotation. The results for healthy controls revealed that force accuracy was lower (higher errors) during external rotator activation (18% of the target torque) compared to internal rotator activation (14% of the target torque). Force steadiness was also lesser (higher CV) during external rotator activation (CV = 11.52% of target torque) compared to the internal rotator activation (CV = 8.28% of target torque). The authors proposed that these significant differences were thought to be related to the starting position of the arm during the task. At a position of 90^{o} external rotation the external rotators were in a shortened position and internal rotators were in a lengthened position. As mentioned previously (section 2.4.2.2), force accuracy is influenced by muscle length. In contrast to Maenhout et al. (2012), Dovers & Powers (2003) did not find significant differences for force accuracy of internal rotators between maximally internal rotated and external rotated position. Though it should be recognised that higher peak torque is produced by internal rotators compared to external rotators and Dover & Powers, (2003) did not normalise their error scores to the target torque.

With respect to injury, most studies examined force appreciation in subjects with shoulder pain due to rotator cuff tendinopathy (Maenhout et al., 2012), subacromial pain/shoulder impingement pain (Bandholm et al., 2006; Benze et al., 2009; Zanca et al., 2010) and in overhead athletes with shoulder impingement (Zanca et al., 2013). One study examined the effect of experimental pain on shoulder abductor force steadiness in healthy subjects (Bandholm, Rasmussen, et al., 2008). These studies will be discussed in further detail below.

In patients with rotator cuff tendinopathy Maenhout et al. (2012) investigated force accuracy and steadiness for both internal and external rotator muscles at 50% MVC. This was compared across affected and unaffected sides and between patient and control groups. The results showed there was no significant difference between sides or groups for force accuracy (relative error) or force steadiness. Both force accuracy and force steadiness were significantly lower for external rotators in comparison the internal rotators in healthy controls and patients. As mentioned above, differences in results between the two muscle groups in force acuity may be attributed to the shortened muscle length of external rotators. The authors highlighted that the subjects reported increased “difficulty” during external rotation force matching test.

The effect of pain on force appreciation was examined by Bandholm and colleagues in two different studies. Bandholm et al. (2006) first examined force steadiness, maximal strength and muscle activation in patients with subacromial pain syndrome. Nine patients with dominant shoulder pain and healthy controls performed isometric force matching at 90^{o} abduction at target forces of 20%, 27.5% and 35% MVC.

Isokinetic force matching was performed at similar target forces from 30^{o} to 120^{o} abduction at 15^{o}/s. The results showed no significant difference for isometric force steadiness at any target force levels between the patient and healthy control group. The patients exhibited significantly lower force steadiness at 35% MVC during concentric contractions when compared to healthy controls. A significant decrease in eccentric force steadiness in comparison to concentric force steadiness was noted in the patient group at 20% MVC. The authors suggested that use of dominant affected shoulder in physical activity and training may have countered the inhibitory influence from nociceptive (group lll and lV) afferents on the motor units of agonist muscles during isokinetic and isometric force matching. Absence of latissimus dorsi activity during initiation or termination of abduction at 35% MVC confirmed that antagonist coactivation did not contribute to decreased force steadiness at that force level. It was concluded that a combination of the above factors may have led to only mild impairment of force steadiness in subjects with subacromial pain.

Similar findings were reported in another study (Benze et al., 2009) where no difference in isometric force steadiness for abductors at 35% MVC was noted between patients (n = 27) and healthy controls (n = 23). Other key findings were that arm dominance did not affect force steadiness and force steadiness at the unaffected shoulder was comparable with the healthy control group. Therefore, the unaffected shoulder could be used as a reference for comparison in investigation of force appreciation at the affected shoulder.

Contrasting results were obtained in the second study by Bandholm, et al., (2008) where experimental pain was induced by injecting 6% hypertonic saline into the supraspinatus muscle. It was reported that induction of muscle pain reduced isometric force steadiness by 21% compared to before pain but the data for force steadiness pre and during pain at different force levels was not given for comparison. Experimental pain also caused small but significant increases in middle deltoid muscle activity during isometric force matching and infraspinatus and lower trapezius during termination of concentric contractions. The effects of experimental pain differed from those observed in patients with chronic subacromial pain from the previous studies (Bandholm et al., 2006; Benze et al., 2009). The authors suggested that different adaptations in the central nervous system may have occurred with chronic pain which were absent in experimental pain condition (Bandholm, Rasmussen, et al., 2008).

Only two studies investigated the isometric force steadiness for internal and external rotators in the presence of shoulder pain (Zanca et al., 2010, 2013). Zanca et al. (2010) first investigated this in female assembly line workers with chronic shoulder pain. The examination of force steadiness was performed at 90^o abduction for internal and external rotation at 45^o and 75^o of external rotation of shoulder at a target force of 50% MVC. No significant difference for force steadiness was found for both muscle groups between affected and unaffected shoulders. The results were also not significant when compared with healthy controls. The authors concluded that daily engagement in upper-body activities in this cohort may have balanced the inhibitory effect of shoulder pain on alpha motor neurons of the internal and external rotator muscles.

In a later study, Zanca and colleagues (2013) investigated force steadiness for external and internal rotators in athletes with impingement symptoms (n = 21) who played overhead sport, asymptomatic athletes (n = 25) and non-athletes (n = 21). The examination was performed with the shoulder in 90° abduction and 90° external rotation at 35% MVIC. There was no significant difference for force steadiness in athletes with impingement symptoms when compared to the other groups. Like their previous study, Zanca et al. (2013) suggested that daily engagement in upper-body activities in this cohort may have balanced the inhibitory effect of shoulder pain.

With respect to shoulder instability, only one study (Saccol et al., 2014) investigated force appreciation in athletes with traumatic shoulder anterior instability (n = 10) and those with SLAP (Superior Labrum Anterior and Posterior) lesion. Both these groups were matched with two age-matched control groups (n = 10). The unaffected shoulder of the injured groups was not examined. An isometric force matching task was performed with the shoulder at maximum achievable external rotation range at 90°abduction with 35% MVIC target torque. The results showed no significant difference for force steadiness between the instability group and healthy shoulders. The SLAP lesion group showed decreased force steadiness for internal rotators in comparison to the control group. The authors suggested that this deficit could reduce their ability to achieve the desired force or produce the intended limb motion during activity.

To date, force appreciation at the shoulder joint after anterior stabilisation surgery has not been investigated. However, research examining joint position sense at the shoulder joint after anterior stabilisation surgery showed impaired joint position sense at the involved side when compared with uninvolved side at approximately 6 months - 2 years after surgery (Fremerey et al., 2006; Rokito et al., 2010; Zuckerman et al., 2003). Furthermore, Fremerey et al. (2006) reported that in overhead athletes a significant correlation was found between ability to return to sports and restoration of joint position sense.

In summary, force appreciation at the shoulder joint is not significantly decreased in patients with chronic shoulder pain due to rotator cuff tendinopathy or subacromial impingement. It was proposed that use of upper body/shoulder and arm in daily activities may have countered the inhibitory effects of pain on the spinal motor neurons. Examination of force appreciation for external rotation and internal rotation at the shoulder in 90° abduction has good reliability. The force steadiness can differ between these two muscle groups especially in position of 90° abduction combined with external rotation. There is a paucity of research regarding force appreciation in shoulder instability, and as mentioned above there are no studies that have investigated this potential impairment in individuals after anterior stabilisation surgery.

While there is limited research related to force appreciation and shoulder instability, there have been notable studies that have investigated this construct at the knee and ankle joints following injury. In the next section these are presented.

2.6.5 Force appreciation at the knee joint

Damage to the anterior cruciate ligament often leads to instability at the knee joint. Anterior cruciate ligament reconstruction (ACLR) surgery is recommended for individuals who wish to return to sports that places high demand on the knee joint (Rice et al., 2021). Studies have examined force appreciation in subjects after ACL injury or ACLR surgery (Perraton et al., 2017a; D. Rice et al., 2021; Telianidis et al., 2014; Ward et al., 2019; Zult et al., 2017). The key focus of research in subjects after ACL injury or ACLR was to examine whether diminished quadriceps force control contributed to impaired force regulation and deficits in neuromuscular control at the knee joint.

A notable study by Ward et al. (2019) examined quadriceps force control in subjects (n = 18) at 8 months after unilateral ACL injury. The quadriceps force matching task was performed with the knee in 60º flexion and required the subjects to closely match a sinusoidal target force signal varying in intensity between 5% and 25% of subject's body weight for 60 seconds. The quadriceps force accuracy was assessed using the RMS error relative to the target torque. The results in the ACL group showed a greater total force-matching error for involved (29% difference, effect size: 0.8) and uninvolved (27% difference, effect size: 0.9) limbs in comparison to uninjured subjects. The difference across these limbs was not significant. The authors hypothesized that bilateral force accuracy deficits in ACL injury population could be related to cross-education effect resulting in neuromuscular alterations after injury. It is unknown whether this effect is specific to lower extremity injuries where most functional activities and sports require bilateral use of both lower extremities. Considering that the force matching task was undertaken with visual feedback, the authors proposed that alterations in the visual or sensory integration regions rather than motor cortex could have contributed to quadriceps force control deficits.

Conflicting results were reported in another study (Zult et al., 2017) where quadriceps force control and other neuromuscular measures were examined in subjects (n = 16) after ACL injury at an average timeframe of 9 months after injury. In this study, isometric force matching was performed at 20% MVC and at a target force of 40Nm for the dynamic task. The results showed that force accuracy and steadiness was not significantly different between ACL patients and active controls. Similarly, no significant difference across sides was observed for force appreciations measures. The contrasting results between the two studies (Ward et al., 2019; Zult et al., 2017) could be due to the difference in the methods used for investigating force appreciation. Perhaps isometric matching of a fluctuating force signal varying in intensity as used in the study by Ward et al. (2019) was more complex than isometric or dynamic force matching at a steady target force used by the other study (Zult et al., 2017) thereby revealing deficits in force control.

From the same research group, three studies (Perraton et al., 2013, 2017; Telianidis et al., 2014) investigated submaximal quadriceps force control during isometric knee extension where subjects matched a moving target on a screen by cyclically increasing and decreasing quadriceps force between 5% and 30% MVIC. The force accuracy was measured by calculating the quadriceps RMS error relative to the target torque. EMG data for quadriceps and hamstring muscles was collected to quantify muscle activation strategies.

In the first study, Perraton et al. (2013) reported that significantly decreased quadriceps force accuracy and greater activation of medial hamstring and vastus medialis was observed in the ACLR group (n = 30) than healthy control participants (n = 30). Based on the quadriceps RMSE and self-reported knee function using Cincinnati Knee Rating Scale (CKRS) they classified participants into two sub-groups. ACLR participants who had decreased force accuracy had significantly better knee function (CKRS = 90.6%, 95% CI = 86.5-94.7) than participants with greater force accuracy (CKRS = 81.2%, 95% CI = 73.0-89.4) (Perraton et al., 2013). This was an unexpected result and the authors thought that this reflected a mal-adaptive neuromuscular strategy adopted by some individuals after ACLR.

In the second study, Telianidis et al. (2014) reported that RMS error in the ACLR group was significantly greater when compared to the control (23 % difference). With regards to muscle activation and quadriceps force accuracy, the results reported by Telianidis et al. (2014) were in line with the results reported in a previous study by the same research group (Perraton et al., 2013) highlighting that increased hamstring muscle activation was associated with improved quadriceps force accuracy in ACLR group. Telianidis et al. (2014) also reported that there was no significant correlation between anterior knee laxity (at 30lbs) and quadriceps RMS error.

Contrasting results were obtained in the third study by Perraton et al. (2017). Increased coactivation of lateral hamstring was associated with worse knee function and greater odds of scoring < 85% on one or more knee functional tests over a year from time of surgery (Perraton et al., 2017). The level of lateral hamstring activation being relatively small, the authors proposed that this could be a protective strategy to protect the ACL graft by decreasing the tibial internal rotation. In the above studies from this research group force accuracy was not compared between ACLR limb and the unaffected limb.

In a recent study Rice et al. (2020) investigated differences across an ACLR surgery and control group performing a submaximal force modulation and force matching task at 25% and 50% MVC. The authors reported that quadriceps force matching accuracy was decreased in ACLR participants compared to the control group. Medial hamstring activation was significantly increased in ACLR group in comparison to the controls, which was also observed in previous studies (Perraton et al., 2013; Telianidis et al., 2014).

In summary, it appears that in ACL deficient participants quadriceps force accuracy is impaired in both affected and unaffected side when compared to healthy individuals. Results were similar for individuals with ACLR surgery. No comparisons were available across injured and uninjured limbs. Interestingly, studies that examined the relationship between overall function and force appreciation were limited and results across studies were contrasting.

2.6.6 Force appreciation at the ankle joint

At the ankle joint, force appreciation was primarily conducted in individuals with chronic ankle instability (CAI) (Arnold & Docherty, 2006; Docherty & Arnold, 2008; Hagen et al., 2018; Kim et al., 2014; Lee et al., 2021; Sousa et al., 2017; Wright & Arnold, 2012). The force appreciation across these studies was tested for ankle evertors and invertors with the ankle in neutral position at 10% and 30% of MVC. Most studies used an ipsilateral isometric force matching method where target forces were initially attained with visual feedback and then reproduced without visual feedback. Similar findings were seen across most studies with decreased force accuracy in CAI groups in comparison to the uninjured population. The absolute error (AE) and variable error was significantly greater for evertors at 10% MVC in those with chronic ankle instability and functional ankle instability (Arnold & Docherty, 2006; Docherty & Arnold, 2008; Sousa et al., 2017; Wright & Arnold, 2012).

Arnold & Docherty, (2006) investigated the relationship between the perceived ankle instability (AII6 questionnaire) and frequency of giving way with eversion force sense in subjects with functional ankle instability. They included a contralateral and ipsilateral force matching protocol for isometric force matching at 10% and 30% MVC. The results showed a significant correlation (ipsilateral matching, r = .58, contralateral matching r = .49) between perceived ankle instability and absolute errors at 10% MVC at the injured ankle. Similarly, the absolute and constant errors at 10% MVC at the injured side were correlated with the giving way frequency (Arnold & Docherty, 2006). These results were not observed for the uninjured ankle. Based on these findings, it was suggested by the authors that in functional ankle instability the injured ankle behaves like an unreliable force sensor. Perhaps central control of force sense does not contribute to sense of instability hence lack differences across sides with respect to correlation analyses (Arnold & Docherty, 2006). The force accuracy was not compared across limbs in this study.

Sousa et al. (2017) reported upon a chronic ankle instability group that was divided into those with mechanical instability on testing and those with a subjective feeling of instability or “giving way” called functional ankle instability. An ipsilateral force matching task for evertor muscles was performed with the ankle in 15^{o} plantar flexion at 20% MVIC, and at 5^{o} and 15^{o} inversion. The results showed increased errors in force matching for the uninjured and injured side in the FAI group at 15^{o} inversion when compared to the control group (injured limb Cohen d = 1.28, uninjured limb Cohen d = 0.76) and mechanical ankle instability group (uninjured limb: Cohen d = 0.76) (Sousa et al., 2017). A trend (p = .03) across affected and unaffected ankles in the FAI group was reported. A small sample size in the functional instability and mechanical instability groups (n = 10 & 14) is a limitation of this study.

In a chronic ankle instability group Lee et al. (2021) had subjects perform isometric inversion and eversion at 10% and 30% MVIC and were instructed to track these target force signals. The results showed decreased force accuracy (RMS error) at 10% MVC for ankle invertors and evertors (Cohen d = 0.65). The force steadiness (standard deviation) showed decreased steadiness for ankle invertors at 10% MVC when compared to an uninjured group. The force accuracy and steadiness were not compared across limbs in the injured group.

In summary, the research examining force appreciation in subjects with chronic ankle instability showed that force accuracy and steadiness is affected at low force levels for evertors at the injured side when compared with the uninjured healthy controls. There was limited support for force appreciation being related to instability/giving way at the ankle. There was no research regarding force appreciation in individuals who have undergone ankle stabilisation surgery.

2.7 Perceived function following glenohumeral joint instability

Questionnaires are used to understand the impact of glenohumeral joint instability on patients' perception regarding various important constructs (quality of life, function, pain, confidence, satisfaction). This information is thought to reflect the success of treatment outcomes and can also be useful to also structure rehabilitation programs and aid decision making regarding return to sports. In this thesis, the key focus was to appreciate whether perceived function was related to force appreciation measure at the shoulder joint. Such findings could be useful to development of new treatments to improve rehabilitation programmes. Widely used questionnaires developed for shoulder instability will be presented in this section.

The Western Ontario Shoulder Instability Index (WOSI) is a disease specific quality of life tool measuring the impact of shoulder instability. It consists of 21 items representing 4 domains: physical symptoms, sports/recreation/work, lifestyle, emotions. The best possible score is 0, which implies improved quality of life and greater recovery. The worst possible score is 2100 which signifies that the patient has extremely decreased quality of life due to shoulder instability. The score from each subscale can be reported separately or converted into a percentage of the total score (Kirkley et al., 1998). The responsiveness of the WOSI at different time points following arthroscopic surgery has been reported in literature (Gerometta et al., 2016; Gottlieb & Springer, 2021; Kemp et al., 2012; Park et al., 2018; Yildiz et al., 2022). At 7-8 weeks follow-up after arthroscopic stabilisation surgery, the mean percentage WOSI score improved from 71% (preoperative) to 50% (postoperative) (Gottlieb & Springer, 2021). The mean percentage WOSI score at 6 months follow-up was reported to be significantly improved from 57% (preoperative) to 17.3% (postoperative) (Yildiz et al., 2022). At 12 months follow-up, the mean percentage WOSI score has been shown to improve significantly from 58% preoperative, to 12% postoperatively (Park et al., 2018). A retrospective study by (Gerometta et al., 2016) showed that at 24 months post-surgery, total WOSI score, specifically related to the item 'sports', was significantly lower in those who had not returned to sports. At 3.5-year follow-up after arthroscopic stabilisation surgery, Dekker et al. (2021) reported that there was a significant difference in the WOSI score in those demonstrating no recurrent instability (Mean WOSI = 255.4) in comparison to those with recurrent instability postoperatively (Mean WOSI = 686). These results indicate that although patient's perception of shoulder recovery advanced from preoperative to one year after surgery, those who had trouble returning to sports or had recurrence of instability, reported decreased perceived function.

Additionally, comparisons between two different types of surgery (open versus arthroscopic) showed the WOSI score to be similar (Mean = 20.61%) at 24 - 48 months post-surgery (Mohtadi et al; 2014, Bottoni et al; 2005). The average cumulative WOSI score (standardised from 0-100 with 100 indicated no shoulder dysfunction) reported at various timepoints from preoperative (48 points), 6 months (78 points), 12 months (84 points), 24 months (85 points) postoperatively was similar in two studies (Hurley et al., 2021; Mohtadi et al., 2014). These results showed that perceived function is still compromised at six months, when most individuals are allowed to return to sports post anterior stabilisation surgery.

Another self-reported outcome measure commonly used in patients with anterior stabilisation surgery is the ROWE score which is 100 points scoring system consisting of three key areas: stability, mobility, and function, with a higher score indicating better function. Park et al. (2018) reported that at one-year follow-up post anterior stabilisation surgery the mean ROWE score increased significantly from 46.0 (preoperative) to 93 postoperatively. The conciseness of this tool makes it feasible to use it clinically. However, it is thought to be limited by only three questions for each of its domains, and overall, it covers only some domains that are thought to be representative of function. Other limitations include it not being as comprehensive as the WOSI which captures aspects of lifestyle, emotions and physical symptoms that influence perceived function.

Recently, the Single Assessment Numeric Evaluation score (SANE) has been utilised in shoulder instability patients. As the name suggests, it is a single patient-reported question reflecting patients’ perceptions on recovery. The best possible score (100 points) representing a completely stable shoulder (Lädermann et al., 2021). Bottoni et al. (2005) conducted a randomised controlled trial and reported that at 36 months post-surgery the SANE score improved significantly from pre-operative (53.0 ± 14.8) to post-operative (92.3 ± 8.1) in the arthroscopic surgery group. The change in open surgery group from pre-operative (52.7) to post-operative (90.6) was also significant (Bottoni et al., 2006).

There is growing evidence that an individuals’ psychological status impacts upon their ability to return to sports at a preinjury level after surgical repair of shoulder instability. Key factors identified to influence the athletes psychological state after injury include fear of reinjury, decreased confidence in the shoulder and fear of movement (Gerometta et al., 2018; Gottlieb & Springer, 2021; Olds & Webster, 2021). The SI-RSI

(Shoulder Instability Return to Sports Index) evaluates the psychological readiness of an athlete. Higher score is predictive of psychological readiness in return to sports after shoulder stabilisation surgery (Gerometta et al., 2018; Rossi et al., 2022). A retrospective study (Gerometta et al., 2018) found that the mean SI-RSI score at 2-year follow-up was significantly higher in patients who returned to play rugby (60.9 ± 26.6% vs 38.1 ± 25.6%). Olds & Webster, (2021) reported a mean SI-RSI score of 44 in patients who had stabilisation surgery but the average timeframe from surgery was not reported. The average SI-RSI score for those who had returned to sports (48.4± 19) versus not returned (44.1 ± 15) was not significantly different in this study (Olds & Webster, 2021). The authors think that this could because the timeframe between returning to sports and recording of SI-RSI in their study was shorter versus that in study by Gerometta et al. (2018). Another study (Rossi et al., 2022) reported that SIRSI had excellent predictive ability for return-to-sports (area under ROC 0.87, 95% CI 0.80-0.93) and a cut off score of >/= 55 was identified for return-to-sports. The authors reported that 79% of patients returned to sports at a median of 6 months from surgery, the median score of those returned to sports was 65 (57- 80) and not returned to sports was 38.5 (35 - 41) (Rossi et al., 2022).

Another frequently used questionnaire to assess pain-related fear of reinjury and beliefs is the TSK (Tampa Scale of Kinesophobia) where higher score represents greater fear avoidance beliefs (French et al., 2007). The impact of kinesophobia on return to sports in patients with shoulder stabilisation surgery was examined only in one study. The mean TSK score at an average follow-up of 61.1 months was 27 points and the total TSK score correlated with returning to preinjury activity (Vascellari et al., 2019).

To date the relationship between perceived function and force appreciation at the shoulder following an injury has not been investigated. However, Fremerey et al. (2006) examined joint position awareness for shoulder internal and external rotation after anterior capsulolabral reconstruction surgery at a mean follow-up of 2.8 years. Criteria including pain, mobility, return to sports and subjective level satisfaction (VAS scale) were assessed. A significant correlation between joint position awareness and ability to return to pre-injury sport level was observed but an r value was not reported.

Although the relationship between perceived function and force appreciation has not been examined at the shoulder previously, this was examined at the knee in individuals with ACLR. Subjects performed a quadriceps force control task at forces ranging between 5 % to 30% MVC. The Cincinnati Knee Rating Scale (CKRS) was used to assess perceived function (Perraton et al., 2013, 2017). In the first study (Perraton et al., 2013) subjects with poor force accuracy for quadriceps had significantly better knee function (CKRS = 90.6%) and subjects with better force accuracy had worse knee function (CKRS = 81.2%). In another study (Perraton et al., 2017a) the Cincinnati Knee Rating Scale (CKRS) and physical performance tests were used to form a test battery to assess knee function. An odds ratio was calculated between knee function and the quadriceps force accuracy (RMS error). The results showed a significant relationship between these two variables (OR: 2.6) indicating that lower quadriceps force accuracy (increased RMS error) was associated with reduced knee function.

There are no studies to date that have examined the relationship between psychological readiness to return to sport using SIRSI and force appreciation after anterior stabilisation surgery. At the knee joint only one study (Ma et al., 2022) investigated the relationship between knee joint movement sense, and readiness to return to sport. In this study, 42 participants greater than 6 months after ACLR were included. Sense of motion at the knee joint, cutaneous sensitivity and return to sports readiness was examined. The K-STARTS test was used to assess readiness of return to sports, and it consisted of ACL-RSI (psychological readiness) and seven physical performance tests. The results showed that movement sense was related to K-STARTS total score (knee flexion: r = -0.316, knee extension: r = -0.321) but not with ACL-RSI (Ma et al., 2022).

The relationship between kinesophobia on force appreciation has also not been investigated in shoulders after anterior stabilisation surgery. Given that force appreciation is examined at low target force levels it is questionable whether the subjects will experience fear during the task.

In summary, patient reported questionnaires are a valuable tool to understand patients' perspective of their quality of life. Additionally, it aids decision making regarding return to sports after anterior stabilisation surgery. There is some evidence indicating that assessing psychological readiness along with return to sports tests is important in individuals' post-surgery at 6 months when they are allowed to resume sports. At present there is no evidence on the relationship between force appreciation and perceived function in individuals with anterior stabilisation surgery. However, there is some evidence at the knee joint that indicates an association between decreased quadriceps force control and poor knee function is apparent. This finding provides the impetus to examine the relationship between these variables after shoulder stabilisation surgery.

2.8 Physical performance tests and force appreciation

There are numerous functional performance tests to assess shoulder function and determine athletes' ability to return to sports after anterior stabilisation surgery. Some of these are sports-specific (e.g., seated medicine ball throw in overhead athletes) and can be used in isolation, but a battery of tests is recommended to replicate the broader range of functional demands experienced by athletes (Juré et al., 2022; Wilk et al., 2020). In order to examine associations between force appreciation and physical performance in tests, physical performance tests that assessed findings across limbs are required. Such tests allow an association between deficits across limbs to be assessed with deficits in force appreciation across limbs and these are reviewed in this section.

The Shoulder Arm Return to Sports Test (SARTS) is a battery of performance tests developed by (Olds et al., 2019) to determine readiness of return of sports after shoulder injury. The SARTS comprises of four open chain and four closed chain tests. In this test battery, BABER, Line Hops, and Side-Hold Rotation are three tests which assess limb asymmetry and the intra-rater reliability ranges between ICC = 0.96 -0.99. The limb symmetry index (LSI) calculated between nondominant, and dominant side was reported as 100% for Side Hold Rotation and Line Hop and 91% for BABER with a significant dominance effect. In a separate study (Olds et al. 2020) normative data for these tests were established in school and elite rugby players.

Other field tests used to assess upper body function with established reliability in overhead athletes include Upper Quarter Y-Balance Test (YBT-UQ) and Seated Medicine Ball Throw (SMBT). The YBT-UQ is a unilateral closed kinetic chain test that screens upper limb mobility and stability. It requires participants to adopt a push-up position with the test hand on stable platform and the other hand on a movable indicator. The participants push the indicator as far as possible in the medial, inferolateral and superolateral directions without losing contact at the three points of stability (test arm and both feet). It is performed on both sides with 3 trials for each direction. The SMBT is performed with participants seated on the ground with back, shoulders and head against the wall and legs extended. The test requires them to throw a 2 kg medicine ball as far as possible without their back, head and shoulders losing contact with the wall. Four throws are performed with 1 minute rest between each trial (Borms et al., 2016). The intra-trial reliability for SMBT was ICC = 0.980, and for YBT-UQ ranged from ICC = 0.924-0.9667. The LSI for YBT-UQ was not reported but the composite score as percentage of limb length for dominant limb was 90.14 ±

7.56, and for nondominant limb was 89.65 ± 6.02. The mean throwing distance for SMBT was 347.77 ± 76.49 (Borms et al., 2016).

The above-mentioned shoulder performance tests have established normative values and LSI for nondominant versus dominant side in healthy athletic population(Borms & Cools, 2018; Olds et al., 2020). The LSI values for these tests in anterior shoulder instability particularly after stabilisation surgery are lacking. A recent study (Juré et al., 2022), examined the validity of a test battery for with regards to return to sports in patients with Latarjet stabilisation surgery. This test battery comprised of SI-RSI and four physical performance tests which included: maximal strength of external and internal rotator muscles (3 trials for each), YB-UQT(3 trials), Unilateral Seated Shot Put (used 3kg medicine ball) and MCKCUEST (3 sets of 15s and 4th maximal trial of 1s). The LSI for dominant versus nondominant side was computed for Unilateral Seated Shot Put and YB-UQT. A coding procedure was adopted to convert the raw scores on these performance tests and SI-RSI to compute a total S-STARTS score of maximal 21 points. The results reported that S-STARTS score had good reliability (ICC = 0.74) and highly sensitive to change. The S-STARTS score was significantly lower in patients (13.5 ± 3.8 points) when compared to control group (16.1 ± 2.7 points) and a significant improvement was noted between 4.5 months (12.8 ± 2.3 points) and 6 months (17.2 ± 2.4 points) postoperatively (Jure et al; 2021). No significant difference was noted for raw LSI scores between groups for the performance tests. A composite score of this kind is useful to monitor an individual's recovery at different time points however, the LSI gives insight regarding deficits across limbs and guides decision making regarding return to sports. In ACL injury it is widely accepted that LSI greater than 90% is an appropriate cut-off score (Thomeé et al., 2012) but inconsistency in reporting of LSI and lack of cut-off values in shoulder performance tests makes it difficult to discriminate individuals at risk of injury from those who made a good recovery after surgery.

From the current literature on shoulder performance tests none of the studies have examined the relationship between force appreciation and physical performance test at the shoulder. In other joints, only one study (Perraton et al., 2017) with ACLR participants has examined the relationship between force appreciation measures with hop tests. The time point for testing was 18 ± 3 months from surgery. Participants in this study performed a quadriceps force matching task which required them to track a force trace ranging from 5 % to 30% with knee flexed at 60^{o}. The quadriceps RMSE relative to target torque was calculated. Three maximum effort hop tests performed. The results showed that reduced quadriceps force control was associated (OR = 2.6 p = 0.002) with LSI < 85% on one or more hop tests (Perraton et al., 2017).

To summarise several physical performance tests are documented in literature to assess shoulder function and aid decision making regarding safe return to sports. It appears a test battery consisting of closed and open kinetic chain tests assessing different constructs such as range of motion, strength, power, and neuromuscular control are more useful. Additionally, it would be most beneficial if these physical tasks can be undertaken unilaterally and hence a limb symmetry index can be generated. While there is no evidence from research of an association between force appreciation and shoulder performance tests, at the knee there is evidence that decreased quadriceps force control has a negative impact on hop tests results following surgery. The SARTS test battery was appropriate to include in the current study because the three tests: BABER, line hops and side-hold rotation from the test battery examine different constructs hence suitable for a cohort involved in different types of sports. It was developed in Auckland with researchers affiliated with the University of Kentucky and there is considerable access to the normative data in relation to rugby which is the main sport played here in New Zealand. Further, this will help to answer the key question being whether there are correlations between differences across limbs in the respective force appreciation variables and the physical tests.

Chapter 3 Methodology

3.1 Introduction

The principal aims of this study were to examine the force appreciation between the operated and non-operated shoulder in individuals who had undergone an anterior stabilization surgery for recurrent anterior instability, at between 6-12 months post-surgery. This study also investigated the relationship between force appreciation and perceived function (using written questionnaires) and physical performance (using Shoulder Arm Return to Sports Test) in this cohort for their operated shoulder.

This chapter includes subject recruitment strategies, the questionnaires utilized to assess perceived function, a description of the experimental procedures including the equipment used, the set-up and instructions given, and finally a section outlining the data analyses and the statistical procedures utilised.

3.2 Study Design

The current study used a cross-sectional inter-limb comparison design. This involved an assessment of participant's force appreciation, perceived function, and physical performance at one time point only, 6-12 months after anterior stabilisation surgery.

The Auckland University of Technology Ethics Committee reviewed and approved the research methodology and study protocol (approval number 20/236 – see Appendix A).

3.3 Selection of participants

3.3.1 Participant recruitment

Participants with anterior stabilisation surgery were recruited via advertising on social media group for physiotherapists, via email through Auckland Branch of Physiotherapy

New Zealand, via advertisements on AUT university student notice boards, and contacting surgeons in the wider Auckland region. The advertisements requested participants between the ages 18 and 45 years who had undergone anterior stabilisation surgery for recurrent anterior instability and were 6-12 months post-surgery (see Appendix B)

The sample size was determined using G*Power and calculations were based on a pilot study in the AUT Biomechanics lab and published research (Saccol et al., 2014). With an alpha value of 0.05 and a beta value of 0.80, to observe a 20% difference in mean scores for force appreciation between limbs, and to detect a significant correlation at the level of r = 0.55, 24 participants were required.

The researcher contacted each participant to screen them for inclusion and exclusion criteria of the study.

3.3.2 Inclusion criteria

- Unilateral anterior stabilisation for recurrent anterior instability
- Recreational athletes aged between 18 and 40 years (change if ethics approval for amendment) who were involved in sports which load the shoulder either directly or indirectly.
- Approximately 6-12 months post-surgery
- Cleared by the surgeon to return to sports

3.3.3 Exclusion criteria

- Previous shoulder stabilisation surgery or other shoulder surgery (e.g., rotator cuff repair, AC joint stabilisation)
- History of shoulder instability on the non-operated side
- Ongoing shoulder pain post-surgery or neck pain that might impair the ability to perform the test tasks.
- Presence of muscle weakness due to nerve injury secondary to traumatic anterior instability
- Rotator cuff repair performed with shoulder stabilisation surgery
- Visual or auditory impairment that might affect the ability to perform the test tasks
- Neurological conditions (e.g., cerebrovascular accident, brachial neuritis)
- Recent physiotherapy or injury to (within the last three months) neck or shoulder (e.g., rotator cuff related pain, AC joint sprain)
- Severe cognitive dysfunction

- Unmanaged respiratory conditions (mild asthma excluded)
- Other medical conditions or physical impairment which may have impeded the participants from doing the physical performance test or could put them at risk during testing
- Unable to provide informed consent

3.4 Procedures

3.4.1 Data collection

Study data were collected and managed using REDCap electronic data capture tools hosted at Auckland University of Technology. REDCap (Research Electronic Data Capture) is a secure, web-based software platform designed to support data capture for research studies (Harris et al., 2009, 2019). The participant information booklet (see Appendix D), consent form (see Appendix C), and questionnaires to collect demographic data (see Appendix E), and perceived function were built into REDCap. Once a participant was deemed to be suitable for recruitment, they received a survey link for the information booklet which gave detailed information regarding the experimental set-up (including aims, rationale, methodology, potential risks, and benefits of the study) along with the consent form. After receiving the consent form, an automated survey link was sent for the other questionnaires. A personalised message confirming the suitable date and time for testing was included with this survey link. If a participant had not completed the questionnaires sufficiently, reminders were sent through REDCap.

During the initial phone call and in the email, the subjects were encouraged to ask questions and were assured that they could withdraw from the study at any stage without facing any consequences.

All testing was performed at the Biomechanics Lab of the School of Clinical Sciences, Auckland University of Technology (AUT) North Shore Campus. All subjects were tested by the primary investigator. The testing was performed in one and half hour session. The participants completed their consent form and other questionnaires prior to the testing session. During the testing session, strength assessment of their shoulder internal and external rotators and force appreciation was completed on the Biodex isokinetic dynamometer, and then participants performed a series of physical performance tests.

3.4.2 Demographic and functional questionnaires

Information was collected concerning age, gender, physical characteristics (weight and height), ethnicity, occupation. The type of sport, and level of play was determined using Degree of Shoulder Involvement in Sports (DOSIS) (Vascellari et al., 2018). All this information was collected through REDCap survey. Specific information related to the etiology of their shoulder instability, frequency, direction, and severity of injury (subluxation/dislocation) was included to determine the type and severity of instability preceding surgery (Kuhn et al., 2011).

Participants also completed questionnaires relating to their perceived function, fear of movement and psychological readiness to return to sport post-surgery. The questionnaires and their psychometric properties are described below.

The Western Ontario Shoulder Instability Index (WOSI) (see Appendix F) consists of 21 items and evaluates quality of life across four domains: physical symptoms (10 items), sport/work function/recreation (4 items), lifestyle function (4 items), and emotional function (3 items). Each question is scored on a 100mm slider (visual analog) scale with a score ranging from no complaints (0) to severe complaints (100). The best possible cumulative score is 0, indicating no limitation, while a score of 2100 indicates severe limitation. A percentage score can be derived from the total score, where a score of 2100 would mean 0% and 0 reflects 100% of normal function. A cumulative score of each domain can also be calculated (Kirkley, Griffin, Mclintock, et al., 1998; Van Der Linde et al., 2017). For this study, the total cumulative and percentage score was obtained. The questionnaire has been shown to be valid and reliable and used to evaluate treatment outcome in patients with shoulder instability. Concerning reliability, ICCs have been reported in a range from 0.77- 0.81 respectively (Kirkley, Griffin, Mclintock, et al., 1998; Van Der Linde et al., 2017). The minimum clinically important difference (MCID) is 220 points (10%) (Bouliane et al., 2014; Dekker et al., 2021; Kirkley et al., 1998).

The ROWE scale (see Appendix G) is an internationally recognised self-reported scoring system assessment of function following Bankart repairs (Jensen et al., 2009; Kirkley, Griffin, Mclintock, et al., 1998; Lädermann et al., 2021; Park et al., 2018). It has four different versions. For this study, we used the first version which was published in 1978 (Jensen et al., 2009; Rowe et al., 1978). The ROWE scale is a 100-point scoring system and consists of three domains: stability, motion, and function. The weighting for each domain differs such that maximum score for stability is 50 points, for motion 20 points and for function 30 points (Jensen et al., 2009; Kirkley et al., 1998). The internal consistency for the ROWE measured by a Cronbach alpha ranged from 0.81 to 0.88, and ICC ranging from 0.65-0.80. It has good correlation (r = 0.609) with WOSI and moderate to good level of responsiveness in the shoulder instability population (Kirkley et al., 1998). The conciseness of this tool makes it feasible to use it clinically.

The Shoulder Instability-Return to Sport after Injury (SI-RSI) (see Appendix H) identifies the psychological readiness of return to sport after an episode of shoulder instability irrespective of their surgery status. It consists of four constructs: performance confidence, reinjury fear and risk, and emotions such as frustration and nervousness related to their shoulder, and rehabilitation and surgery after injury (Olds & Webster, 2021). The SI-RSI includes 12 questions with an 11-Likert scale in the form of blocks to be ticked from 0 to 10. The total score is obtained by adding all the 12 responses and a percentage score is calculated. High scores correspond to a positive psychological response (Gerometta et al., 2018; Olds & Webster, 2021; Rossi et al., 2022). Participants are asked to rate their responses to each question with reference to their main sport prior to injury. Validity has been confirmed by Gerometta et al. (2018) and high reliability was reported with an ICC coefficient of 0.93, CI (0.89-0.96).

The Tampa scale of Kinesophobia (TSK) (see Appendix I) is the most frequently used tool to measure pain-related fear of movement or fear of re-injury (Eshoj et al., 2019; French et al., 2007; Vascellari et al., 2019). The original scale is a 17-item version with each using a four-point Likert scale. The total score ranges between 17 to 68 (worst score). TSK scores above 37 represent high fear of re-injury (Eshoj et al., 2019). The TSK-17 has demonstrated to have good internal consistency with alpha =0.84, (French et al., 2007) and the reliability reported is 0.86 (0.79-0.91) (Eiger et al., 2023).

3.4.3 Rehabilitation programme evaluation

The participants were interviewed upon arrival about the structure of their rehabilitation program. This was to get an understanding of the type of exercises they had performed after surgery. The American Shoulder and Elbow Therapist (ASSET) guidelines (Gaunt et al., 2010) for rehabilitation after anterior stabilisation surgery were referred to for an informal evaluation of the quality of rehabilitation without any intention of psychometric analysis. The rehabilitation program was classified into four categories: Mobility, strength, neuromuscular and sports specific. Each category was graded ‘fair’ or ‘good’ based on type of exercises introduced in each phase and progression of exercises through sets and repetitions in different phases of the rehabilitation. For example, strengthening exercises were graded ‘fair’ if external and/or internal rotators strengthening exercise progressed to 90º abduction from week 12 – 24, through range, but did not have emphasis on progression through increase in volume and intensity of strengthening, had less focus on scapular muscle and other upper body strengthening, and did not include plyometric exercises in individuals returning to overhead sports/work requiring upper extremity power. This also gave an idea whether the rehabilitation was structured specific to an individual’s sporting demand (Gaunt et al., 2010). Neuromuscular exercises included: scapular and glenohumeral setting and control exercises, exercises that challenged dynamic stability at the shoulder and scapular muscles (Eshoj et al., 2017; Gaunt et al., 2010; Gibson, 2004). It was noted if such exercises were included and progressed in the rehabilitation. If only one of these exercises were included but not progressed through rehabilitation, it was graded as ‘fair’ focus on neuromuscular exercises.

3.4.4 Strength assessment

At the testing session, a preliminary assessment of active and passive range of motion at the shoulder and clinical tests for anterior apprehension were performed. Then isometric strength assessment of their shoulder internal and external rotators on a Biodex isokinetic dynamometer (Biodex Medical System, Inc, NY, USA) was performed. The subjects were seated with their shoulder at 90º abduction in the scapular plane and at external rotation range achievable with the elbow at 90 degrees of flexion. The testing arm was supported in the above-mentioned position in a custom-built attachment of steel with a forearm support which was attached to the Biodex. The trunk and hips were stabilised with straps (see Figure 3.1). The unoperated side was tested first so that the subjects became familiar with the testing. For initial warm-up, participants performed a self-selected number of submaximal activations of shoulder muscles at 25%, 50%, and 75% MVC on the isokinetic dynamometer testing. When the participants were ready, they were asked to exert maximum isometric force in internal and external rotation directions. Verbal encouragement was provided during the MVC test with specific instructions to push as hard as possible (McNair, 1996). Three repetitions were performed for each movement direction, each trial lasting for approximately four seconds with a five second rest between the trials. The maximum torque recorded across these trials was utilised to determine the target torque for force appreciation testing. These procedures have been shown to be reliable (ICC: 0.981 for internal rotation and 0.978 for external rotation) (Dover & Powers, 2003).

3.4.5 Force appreciation assessment

Force appreciation was assessed by an isometric force matching task for internal and external rotation in the affected and unaffected shoulder. The target torque level was set at 35% MVC of the limb tested. A customized computer-based program was built within the software application DasyLab (Data Acquisition System Laboratory, Company: National Instruments, Ireland Resources Limited). In this program a channel was dedicated to the target torque, and this was presented to the participant as a line from left to right at the mid-point of a computer screen height. A second channel in the software presented the participant's generated torque on the computer screen. Additionally, there was an external light visible next to the screen. Participants were instructed that when they saw this light illuminate, they should exert a torque as quickly as possible to reach the target torque line and then to hold it steady at that level for 15 second period. The switch for the light was kept out of participants vision and did not make a sound when pressed so they could not anticipate the timing of light being switched on. The external light signal was also collected as a channel in the software to provide a starting point in the data. The analogue to digital system utilised was an instrument 100B (GW Instruments Inc, Charleston, MA 02129, USA), and all three channels were sampled at 1000 Hz (See Figure 3.2). The participants were given seven familiarisation trials to learn the task. The number of practice trials and the protocol was established from a pilot study in our biomechanics laboratory. A nonlinear regression approach was utilized to determine when stability of the variables of interest occurred. The pilot study was undertaken in 10 individuals including participants with instability of the shoulder joint. Following the seven practice trials, three further trials were performed, and the mean of these data were used in the analyses, resulting in ICC values above 0.80.

From the data collected in DasyLab, the following three variables were calculated (See Figure 3.2):

a) RMS error: this is a measure of the error between the target torque and the generated torque across a 10 second epoch beginning at the point at which the generated torque was within 10 percent of the target line for at least two consecutive seconds. It was calculated by taking the target torque level and subtracting it from the torque generated by the participant and thereafter the root mean square was calculated, and that result was divided by the target torque. This measure is commonly utilised (Magni et al., 2021; Perraton et al., 2017; Rice et al., 2021; Rice et al., 2015; Ward et al., 2019) and its reliability was established previously (Rice et al, 2015).

b) Time to steadiness: this provided a temporal measure starting from the time the torque was generated (<1 Nm) to the point that the participant's torque was within 10% percent of the target torque for at least 2 seconds. A similar variable was utilised by Benze et al. (2009).

c) Force steadiness: this is a measure of the variation in the participant's generated torque across a 10 second epoch commencing at the same point described above for RMS error. The standard deviation provided this measure, and it was also standardised to the target torque. Its reliability has been established in previous research (Bandholm et al., 2006; Bandholm, Rasmussen, et al., 2008; Benze et al., 2009; Hortobágyi et al., 2004).

Figure 3. 1 The participants' position during the maximum effort strength test and force appreciation test in the Biodex lab.

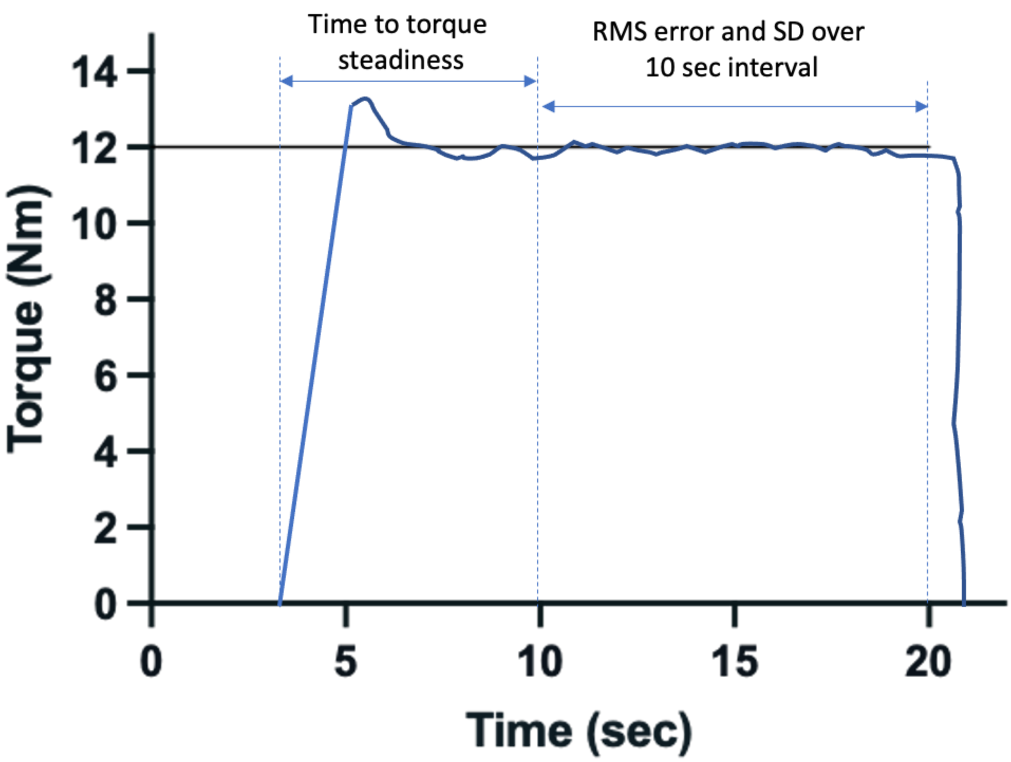


Figure 3. 2 Variables used in analyses of force appreciation traces. Solid black line is the target force (35% MVC). RMS = root mean square; SD = standard deviation; MVC = maximal voluntary activation

3.4.6 Physical performance tests

The Shoulder Arm Return to Sports test battery (SARTS test) replicates some of the demands put upon the shoulder in athletic activities and is used to assess patient's readiness to return to sport. The reliability of this test has been established (Olds et al., 2019). In the current study, only three out of eight tests from this battery allowed us to compare the affected and unaffected side and did not require prior practice. All three tests had good psychometric properties, the intra-rater reliability ranged between 0.78(95% CI 0.63-0.88) and 0.96 (95%CI 0.92-0.98) while the inter-rater reliability ranged between ICC = 0.96 (95% C1 0.94-0.98) and ICC= 0.99 (95% CI 0.98-0.98) (Olds et al., 2019). For all the tests, the unaffected side was tested first. All tests were performed for 1min, recorded with a stopwatch and the repetitions performed were counted with a hand-held counter. A rest period of 1min was given between testing across limbs for each test.

a) Ball abduction external rotation test (BABER): This test required the participant to hold a 3kg medicine ball at their shoulder with the elbow bent (Fig 3.3) and then extend their arm out to 90 degrees of shoulder abduction with elbow fully extended (Fig 3.3). The participant then brought the ball back to the shoulder (Fig 3.3) before extending the arm overhead to 180 degrees of shoulder flexion (Fig 3.3). If the participants failed to fully extend the elbow, or the hand was not brought back to the shoulder at the mid position, or if they dropped the ball, the repetitions were not counted. This test was performed for each individual limb. A rest period of 1min was given between testing of each limb. The limb symmetry for BABER was 91% with significantly decreased scores on non-dominant side ($p< 0.01$) (Olds et al., 2019).

b) Side-hold rotation test: The starting position of the participant for this test was in a side plank position with weight balanced on one hand and both feet on a line drawn between them (Fig 3.4). The participant rotated their body onto their toes such that the pelvis was parallel with the floor, crossed the top hand across the line between the weight-bearing hand and the feet (Fig 3.4) and returned to the start position (Olds et al., 2019). If the participants supported their weight on their moving hand, or if the hips did not rotate so that the pelvis was not parallel to the floor or if they did not return to the start position with arms in full horizontal extension between repetitions, the repetitions were not counted. The limb symmetry was 100% with no significant difference between two sides (Olds et al., 2019).

c) Line hop test: This test was performed on a mat 0.5cm thick. A 3-inch athletic tape was fixed lengthwise along the centre of the mat. At the start of the test, the participants were on their knees with the right hand on the right of the athletic tape (Fig 3.5). They were instructed to keep their hips extended as they hopped their hand over to the other side and back to the start position to complete one repetition. Repetitions were not recorded if the participant's hand touched the centre tape, or they were unable to hop across the line and back or were not able to maintain their balance during this task. The limb symmetry was shown to be 100% with no significant difference between two sides. (Olds et al., 2019).

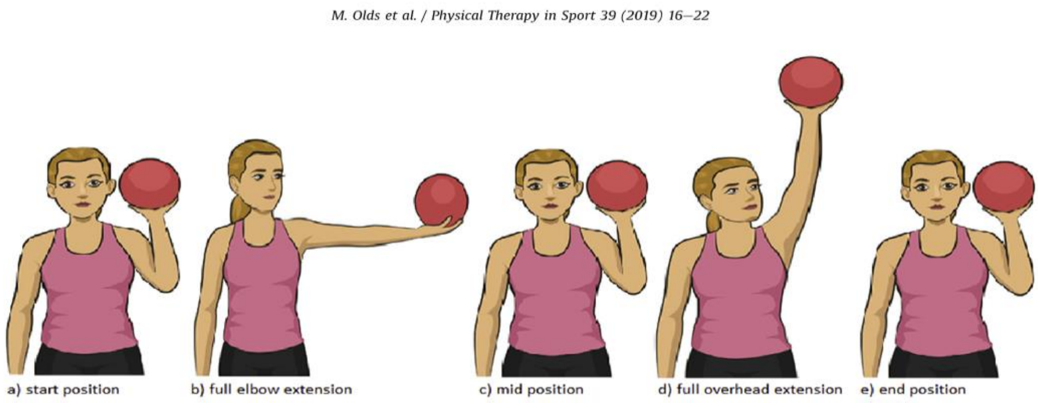


Figure 3. 3 BABER test for the affected and unaffected shoulder

Figure 3. 4 Side-hold rotation test for the affected and unaffected shoulder

Figure 3. 5 The Line hop test for the affected and unaffected shoulder

3.5 Data Analysis and Statistics

The IBM Statistical Package for Social Sciences (SPSS) software program version 29.0 was used for data analysis. Data was checked for errors and outliers using descriptive analyses, box plots and Grubb's test. Normality of data was checked using combination of kurtosis and skewness values, histogram plots and normal Q-Q plot and Shapiro- Wilks test. For all the above tests, and alpha level of 0.05 was set as the level of significance.

A paired sample t-test was performed to examine differences between the affected and unaffected limb for peak torque generated on the Biodex for internal and external rotators, force appreciation and the BABER physical performance test variables. An additional post hoc statistical test was undertaken on the data from the BABER test. It has been reported by the developer (Olds et al., 2019) to have a limb dominance effect indicative of a nine percent higher score on the dominant limb in subjects without injury. As data prior to injury/surgery was not available to identify whether this effect was in place within our cohort, an independent t-test was performed to provide some evidence that dominance may not influence the Limb Symmetry Index (LSI) for BABER test in the current cohort. Specifically, it tested whether those subjects with an injury on their non dominant limb had greater deficits in this performance test than those who damaged their dominant limb.

The Pearson product-moment correlation coefficient (or if data were not normally distributed a Kendall's Tau calculation) was used to examine the relationship between the LSI for force steadiness measures (accuracy and steadiness) and perceived shoulder function (WOSI and ROWE) and a single shoulder performance test (BABER).The rationale for exploring this particular relationship was that this physical performance test involved lower force levels combined with elements of motor control and coordination, as compared to the other physical performance tests which were primarily power tests involving greater loading. In respect of multiple correlations being generated across these variables, the percent error rate (Ottenbacher, 1991) was 20%, indicating that 20% of the results were due to chance.

Chapter 4 Results

4.1 Introduction

This chapter is divided into four sections. Section 4.2 outlines the demographic details of those who participated. Section 4.3 presents the results from the force appreciation testing on the operated and unoperated (stable) shoulder. The next section (4.4) is related to the second research question and presents the findings regarding the relation between force appreciation and perceived function and physical performance tests.

4.2 Participants

Twenty-five participants were recruited who had undergone anterior stabilisation surgery 6-12 months previously [Note: two participants were at thirteen months from date of surgery but met all the inclusion criteria hence were included]. The COVID pandemic with its repeated lockdowns here in Auckland affected the recruitment/testing of participants hence the inclusion criteria were expanded to include participants between 17- 42 years and those with open anterior stabilisation surgery. Additionally, between lockdowns, the primary reason given by participants not wanting to participate was the increased likelihood of acquiring the virus in the university environment.

Twenty-one males and four females with mean age 24 years (+/- 6) ranging from 17-42 years were recruited. The participants had a mean height of 171.8 cm (+/- 36.6) and mean weight 78.4 kg (+/- 20.6). The mean time from surgery was 7 months (+/- 2) ranging from 6-13 months. Twelve of the 25 participants had surgery on their dominant shoulder. Of the 25 participants, two had Latarjet surgery, nine had open anterior stabilisation surgery, and fourteen had undergone arthroscopic Bankart repair with inferior capsule shift. Only one participant had remplissage performed with arthroscopic surgery. All had been cleared by their surgeon to return to sports and 80% (20/25) had returned to play/sports at pre-injury levels and 20% had not returned at the time of testing. Those who had not returned to play were engaged in formal rehabilitation with the aim of returning to training and play for their pre-injury sport within the month following testing. See Table 4.2 for evaluation of the rehabilitation programme. Forty-four percent of participants played sports recreationally, 52% percent played at lower competitive level, and 8% percent were elite athletes (national level competition) at the time of testing.

Concerning perceived function and wellbeing, the mean raw WOSI score was 535 (SD = 320) and the mean percentage score was 25% (SD = 15). The mean TSK score was 35.6 (SD = 4.4). The mean percentage SI-RSI score was 59 (SD = 21). The mean ROWE score was 84 (SD = 13). See Table 4.3 for results.

The isometric strength measures across the affected and unaffected shoulder are displayed in Table 4.4. There was significant deficit ($p<0.05$) between the isometric internal rotation strength between affected and unaffected shoulder with a percentage deficit of 14.3%. Similarly, a significant deficit ($p <0.05$) of 23% was demonstrated for isometric external rotation strength.

The physical performance test measures are displayed in Table 4.5. There was no significant difference between the affected and unaffected side for BABER ($p > 0.05$), side-hold rotation ($p > 0.05$) and line hops ($p > 0.05$) tests.

Table 4. 1 Demographic data of participants

	Anterior stabilisation surgery group		
Number of participants			
- Male	21		
- Female	4		
Ethnicity			
- NZ Pakeha	19		
- NZ Maori	2		
- Pacific	3		
- Asian	1		
Age			
- Mean (SD)	24.64 (6.2)		
- Range	17-42		
Height (cm)			
- Mean (SD)	171.8 (36.6)		
Weight (Kg)			
- Mean (SD)	78.4 (20.6)		
Time since surgery (months)			
- Mean (SD)	7.8 (2.1)		
- Range	6-13		
Type of surgery			
- Latarjet	2		
- Open anterior stabilisation	9		
- Arthroscopic Bankart repair	14		
Pre-injury sports		Level of play	
High demand	40%	Recreational	44%
Moderate demand	24%	Low-level competitive	52%
Low demand	28%	Elite	8%
Return to sports			
- Yes	80% (20/25)		

Table 4. 2 Evaluation of the rehabilitation programme

Rehabilitation	Good	Fair
Range of motion	96%	4%
strength	36%	64%
Neuromuscular	4%	96%
Sports specific	4%	96%

Table 4. 3 Perceived shoulder function from subjective questionnaires for participants post anterior stabilisation surgery

	Mean (SD)
WOSI (%)	
- Lifestyle	19 (11)
- Physical	9 (7)
- Recreational	26 (21)
- Emotional	38 (28)
Total	25 (15)
SIRSI (%)	59 (21)
TSK	36 (4.4)
ROWE	84 (13)

Notes: WOSI: Western Ontario Shoulder Instability Index; SI-RSI: Shoulder Instability Return to Sport after Injury; TSK: Tampa Scale of Kinesophobia;

Table 4. 4 Isometric Muscle Strength Testing (Internal Rotators and External Rotators)

	Affected side (Nm) Mean (SD)	Unaffected side (Nm) Mean (SD)
Internal rotators	37.0 (13.5)	43.0* (13.6)
External rotators	16.3 (5.5)	21.3* (7.0)

Table 4. 5 Physical Performance Tests across limbs

	Affected side (repetitions) Mean (SD)	Unaffected side (repetitions) Mean (SD)
BABER test	10.8 (5.2)	11.1 (4.3)
Side hold rotation test	12.1 (6.5)	12.8 (6.2)
Line Hop	24.2 (11.8)	24.7 (12.5)

4.3 Force appreciation at affected and unaffected shoulders

A significant difference ($p < 0.05$) was found for force steadiness normalised to target torque (%SD to target torque) for internal rotators between the affected (mean = 2.8, SD = .64) and unaffected shoulders (mean = 3.1, SD = .76). Cohen's d effect size was -0.47. A significant difference was also observed for force steadiness for external rotators between the affected (mean = 5.5, SD = 2.3) and unaffected (mean = 4.6, SD = 1.4) shoulders. Cohen's d effect size was .42. See Figure 4.1 & 4.2. No significant differences ($p > 0.05$) were observed for force accuracy and torque rise to steadiness measures between the affected and unaffected shoulders.

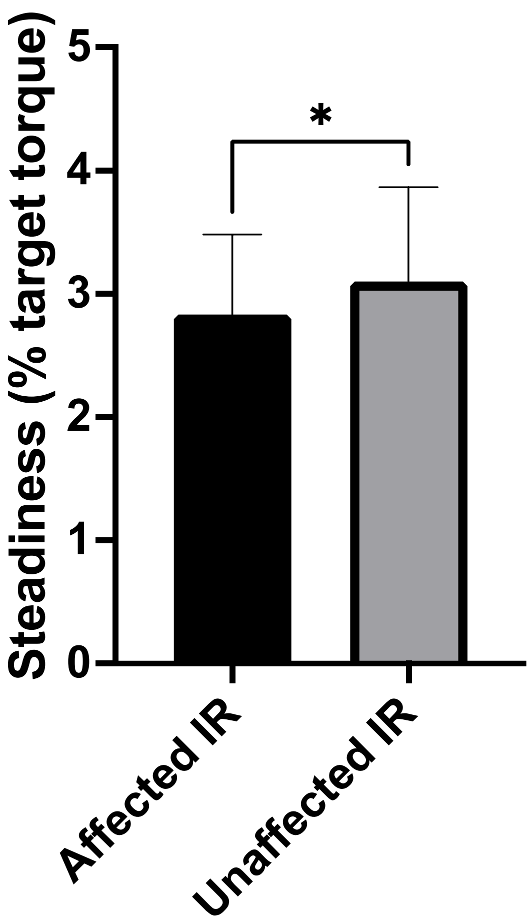


Figure 4. 1 Force steadiness (% target torque) for Internal rotators (IR) of the affected and unaffected shoulder. Data are means and standard deviations. * Indicates p < .05 across affected and unaffected shoulders.

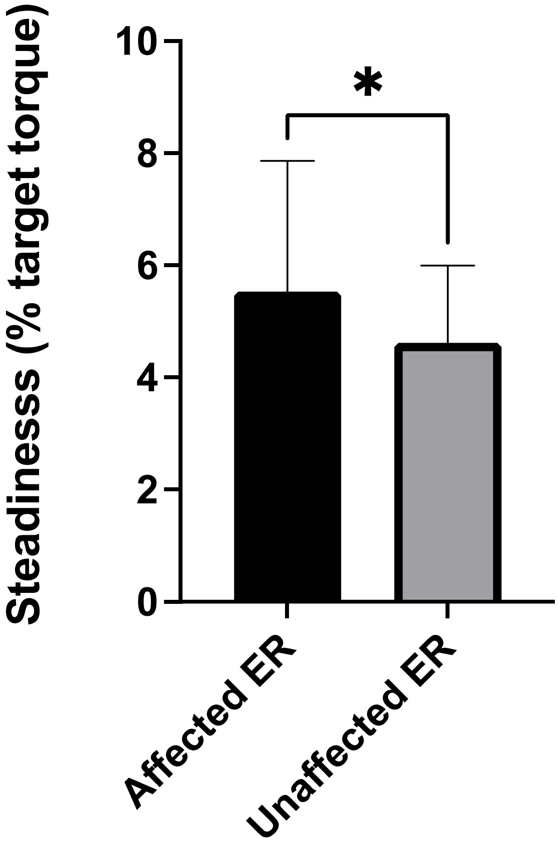


Figure 4. 2 Force steadiness (% of target torque) for External rotators (ER) of the affected and unaffected shoulder. Data are means and standard deviations.
*** Indicates p < .05 across affected and unaffected shoulders.**

4.4 Relationship between force appreciation and perceived function and physical performance tests

The association between force appreciation and perceived function and physical performance tests was examined using Pearson Correlation/Kendall-Tau Coefficients. A significant negative correlation was demonstrated between the LSI for external rotator force accuracy (LSI % RMS of target torque) and the WOSI score (K-Tau = -.34, $p < 0.05$). This indicated that increased deficit across limbs in force matching errors for external rotators was associated with decreased perceived function measured by WOSI. A significant correlation was observed between LSI for internal rotator force accuracy (LSI % RMS of target torque) and the ROWE score (K-Tau = .32, $p < 0.05$). This indicated a lesser deficit across limbs in force matching errors was associated with improved perceived function measured by the ROWE. For force steadiness, a significant correlation was observed between the LSI for internal rotator force steadiness (LSI % SD of target torque) and the ROWE score (K-Tau = .34, $p < .05$). This indicated if the deficit across limbs in force fluctuations was less, it was associated with a better ROWE score. Of note with this association, (See Figure 4.4) there was an outlier (identified by Grubbs test) for which there was no good reason to remove. Kendall's Tau was 0.41 ($p < 0.05$) when the outlier was not included. In contrast, when it was included the Tau value was reduced to 0.32 ($p < 0.05$). No significant correlations ($p > 0.05$) were observed between force appreciation variables and the physical performance tests (See Table 4.6 for results.)

Table 4. 6 Pearson/Kendall's Tau correlations between perceived function and physical performance tests with force appreciation variables

Variables	R/K-Tau	p-value
WOSI & LSI % RMS of target torque IR	-0.22	0.287
WOSI & LSI % RMS of target torque ER	-0.34*	0.032
WOSI & LSI % SD of target torque IR	-0.17	0.423
WOSI & LSI % SD of target torque ER	-0.34	0.092
ROWE & LSI % RMS of target torque IR	0.32*	0.035
ROWE & LSI % RMS of target torque ER	0.04	0.849
ROWE & LSI % SD of target torque IR	0.34*	0.025
ROWE & LSI % SD of target torque ER	0.36	0.074
LSI BABER & LSI % RMS of target torque IR	-0.23	0.120
LSI BABER & LSI % RMS of target torque ER	0.08	0.604
LSI BABER & LSI % SD of target torque IR	-0.16	0.279
LSI BABER & LSI % SD of target torque ER	-0.09	0.540

Notes:

R: Pearson's correlation coefficient

K-Tau: Kendall's Tau

#This Kendall's Tau changed from .41 to .32 when an outlier remained in the dataset.

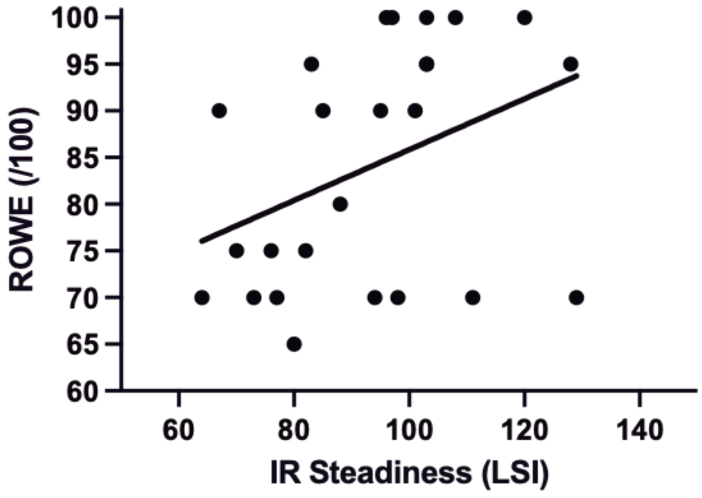


Figure 4. 3 The association between ROWE questionnaire and Internal rotators (IR) force steadiness expressed as a Limb Symmetry Index (LSI).

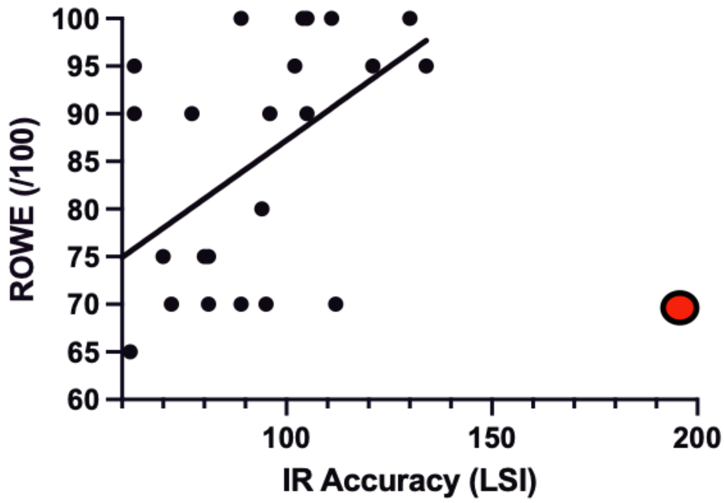


Figure 4. 4 The association between the Rowe questionnaire and Internal rotators (IR) force accuracy expressed as a Limb Symmetry Index (LSI).
Note: In the right lower aspect of the Figure is an outlier (identified by Grubbs test) for which there was no good reason to remove. The line of fit shows the association with the outlier not included in the data. Kendall's Tau was 0.41 (p <

0.05). In contrast, when included notable leverage was apparent and the Tau value was reduced to 0.32 (p < 0.05).

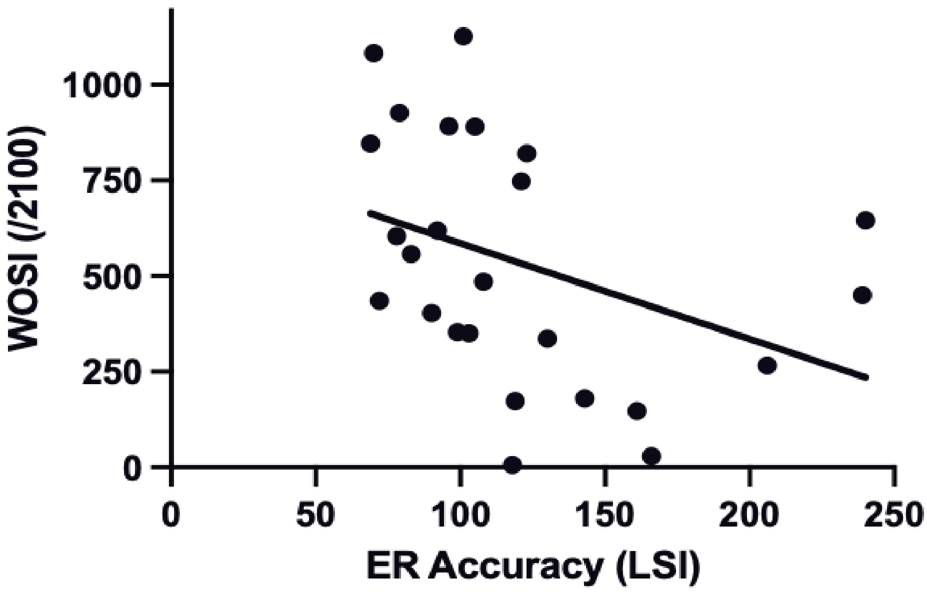


Figure 4. 5 The association between WOSI questionnaire and External rotators (ER) force accuracy expressed as a Limb Symmetry Index (LSI).

Chapter 5 Discussion & Conclusions

5.1 Introduction

Force appreciation in individuals with anterior shoulder stabilisation surgery has not been investigated previously, hence the degree of impairment of this proprioceptive element is not known. The primary question was to investigate whether there was a difference in force appreciation across the affected and unaffected shoulder in this cohort. The main finding showed that that from a statistical perspective, force steadiness was significantly different between the two limbs for internal and external rotator muscles. Additionally, of secondary interest was the association of force appreciation with perceived and performance-based function. These results showed that those individuals with higher LSIs for force accuracy in external rotators had higher perceived function, as measured by the WOSI. Similarly, significant associations were observed for force accuracy and force steadiness LSIs of the internal rotators with perceived function, as measured by the ROWE. These findings are discussed in further detail below. Thereafter, limitations, conclusions and recommendations for future research are presented.

5.2 Participants

The mean age of participants was 24 years which was in line with previous studies (Bohu et al., 2021; Bottoni et al., 2006; Hurley et al., 2021; Mohtadi et al., 2014). The average time from surgery was 8 months which was comparable to that in the retrospective study by Bohu et al. (2021) which included participants with Latarjet surgery. Our cohort was mixed consisting of arthroscopic and open anterior stabilisation surgery. As mentioned in the results section, the inclusion criteria were amended to include both open and arthroscopic surgery because of a lack of patients having surgery due to limited sporting activities being performed when COVID 19 lockdowns were in place. Additionally, patients were more reticent about coming to the university for testing due to concerns related again to COVID 19. However, the extended recruitment criteria are not an unreasonable change as clinical outcomes have been reported to be comparable between the two types of surgery at short-term (2 -4 years) in two randomised controlled clinical trials (Bottoni et al., 2006; Mohtadi et al., 2014).

The percentage of males recruited was 84% and females was 16% which is comparable to other studies (Bohu et al., 2021; Bottoni et al., 2006; Mohtadi et al., 2014; Rossi et al., 2022). The dominant shoulder was affected in 48% of participants which is like that of Mohtadi et al. (2014) but differs from some other studies where the number of dominant shoulder surgeries was higher (Cordasco et al., 2020; Gottlieb & Springer, 2021; Vascellari et al., 2019). This may be because those playing sport with overhead throwing are more likely to seek surgical treatment as anterior instability in an overhead position impacts their ability to play the sport (Harada et al., 2022).

It was difficult to compare the sporting demand on the shoulder of this cohort to other studies. One retrospective study recruited participants involved only in overhead sports (Bohu et al., 2021), and in others sporting level was categorised as collision or contact sports (Mohtadi et al., 2014; Rossi et al., 2022). We utilised the Degree of Shoulder Involvement in Sports (DOSIS) to determine the sporting demand on the shoulder. This scale takes into consideration type of sport, frequency of playing and level of sport and has adequate validity and responsiveness (Vascellari et al., 2018). Based on this scale pre-injury, 40% participants were involved in high demand sports, 24% in moderate demand and 28% in low demand sports. Considering the level of sports, 44% played recreationally, 52% played at a low level of competition and 8% played at elite level. The sporting demand reported in our study is comparable to that of Vascellari et al. (2019). The percentage of participants returning to sports was 80% and those who had not returned was 20%. This aligns with that reported in previous literature (Bohu et al., 2021; Cordasco et al., 2020; Hurley et al., 2019; Rossi et al., 2022). In the current study, 36% returned to sports at pre-injury or similar level at 6 months, 20% returned at less than 6 months and 24% returned between 6-12 months. The median timeframe of return to sports reported in literature is 6 months (Cordasco et al., 2020; Hurley et al., 2019; Rossi et al., 2022). Those who had not returned to sports were engaged in rehabilitation with the intention of resuming sports training within the next 2 months.

The post-operative rehabilitation protocol for the surgery undertaken is relatively standard across most developed countries and focuses on range of motion and strengthening of shoulder and peri-scapular muscles, but also includes neuromuscular and sport specific exercises (Bohu et al., 2021; Bottoni et al., 2006; Gerometta et al., 2016; Gottlieb & Springer, 2021a; Mohtadi et al., 2014; Rossi et al., 2022; Vascellari et al., 2019). It was apparent that the majority of our cohort received fair levels of strengthening (64%), but good level in range of motion exercises (96%). However, neuromuscular and sports specific exercises were not universally utilised at similar levels with majority of participants receiving a fair level (96%) of such exercises and very few participants (4%) had a good focus on neuromuscular and sports specific exercises in their rehabilitation programme. This was surprising since both exercise modes are promoted strongly following lower limb surgeries such as ACL reconstruction, where there is notable evidence (Ebert et al., 2018) for their inclusion providing improved rehabilitation outcomes. One key factor leading for this discrepancy between the degree of different constructs within the rehabilitation programme is a lack of clarity regarding definition of neuromuscular type of exercises in shoulder rehabilitation. This may lead to considerable variation in the introduction of such exercises in different phases of rehabilitation (Coyle et al., 2022). It is also likely that funding constraints within the New Zealand health system prevents implementation of a supervised rehabilitation programme which is often required for delivering a good neuromuscular exercise program.

It was difficult to compare the perceived function scores in our cohort to other studies where the scores were taken at different time-points during the recovery. Our cohorts mean percentage total score on WOSI was 25% (lower reflects better function), and this was higher than the mean score of 12% at 12-month follow-up after arthroscopic anterior stabilisation surgery reported by Park et al. (2018) but lower than 50% reported by Gottlieb & Springer, (2021) for a cohort at 7-8 weeks post arthroscopic stabilisation surgery. The mean ROWE score was 84 (higher reflects better function) for our cohort, which is slightly lower than the 93 points reported by Park et al. (2018). In another study (Lädermann et al., 2021) the ROWE score at 6-month follow-up for a non-operated and an operated cohort (Latarjet and arthroscopic stabilisation surgery) was 86. Overall, the results from both perceived function questionnaires showed high function for the cohort in the current study.

The psychological readiness of return to sport was assessed through SI-RSI scale where a total score of 120 represents full confidence in return to sports. Our mean score was 71 which was like that reported by Bohu et al. (2021) (mean = 70) at 8-month follow-up. This was well above the median cut-off score of >/= 55 which is predictive of readiness to return to sports (Rossi et al., 2022). Related to psychological readiness to return to sport, our cohort's mean TSK-17 (kinesophobia) score was 36, which was higher than that reported by Vascellari et al. (2021) at 5-year follow-up (mean = 27) and the participants in Vascellari's study who returned to pre-injury level of sports had lower scores on TSK-17 (mean = 23). Of note TSK scores above 37 represent high fear of re-injury (Eshoj et al., 2019).

Our three physical performance tests have not been assessed in a patient cohort after anterior stabilisation surgery. Using an uninjured cohort, Olds et al. (2019) reported that the LSI for the side-hold rotation and line hops was 100%, but for the BABER a dominant effect was found with an LSI of 91% indicative of a less repetitions performed in the non-dominant limb. Our mean LSI for side-hold rotation was 86%, BABER was 87% and line hops was 87%. A comparison with LSIs for similar type of tests (Yildiz et al., 2022), indicated that our cohort were performing poorly for 8 months post-surgery. Of note, based on lower limb return to sport's criteria (Thomeé et al., 2012) 52% participants in our cohort who played moderate and low demand (non-contact) recreational sport would have failed and 40% percent playing high-demand (contact and collision) sports would also have failed. Thus, it would be recommended that further rehabilitation be continued prior to return to recreational non-contact sport.

In summary, our cohort consisted of participants mainly involved in low level competitive or recreational sports. The average follow-up after surgery was at eight months which is much earlier than that reported in other studies. The perceived function scores were comparable to those reported for a similar time-point but scores on physical performance tests were not acceptable and indicated that many participants would benefit from further rehabilitation to achieve full functional recovery.

5.3 Maximal isometric strength measures

The current study examined maximal voluntary isometric strength of shoulder internal and external rotators to obtain the target force levels for force appreciation testing. While comparison of strength across shoulders was not the primary purpose, the 23% deficit in external rotation strength across limbs was considered high and worthy of some discussion, particularly as all participants had been cleared to return to sport by their surgeons. Not surprisingly, this deficit was less than the 38% percent reported by Gottlieb & Springer, (2021) who examined isometric strength at seven to eight weeks after arthroscopic anterior stabilisation surgery, but similar to Yildiz et al. (2022), who assessed a cohort at 6 months following arthroscopic anterior stabilisation surgery. Some studies utilised isokinetic testing at an angular velocity of 60°/s. For instance, the deficit in external rotation strength reported by Edouard et al. (2012) was 17% at 6 months post Latarjet surgery, while at the same time point post arthroscopic anterior stabilisation surgery, Yildiz et al. (2022) reported a 23 % strength deficit. In contrast, at nine months post arthroscopic anterior stabilisation surgery, Amako et al. (2017) observed a much lower deficit of 12%.

In a recent retrospective study by Ishikawa et al. (2023) that measured the cross-sectional area of the rotator cuff muscles with MRI, external rotators (infraspinatus + teres minor) had a greater deficit (lesser cross-sectional area) (8.4 ± 2.4 cm^2) compared to subscapularis (internal rotator = 9.4 ± 2.5 cm^2) in subjects with anterior instability. This was in line with our findings with a lesser deficit (14 percent) for the internal rotators. There is evidence that recurrent anterior dislocations cause lengthening and thinning of subscapularis muscle tendon (Tuoheti et al., 2005). Considering its role as an internal rotator, in resisting movement into external rotation, particularly when the upper arm is above the horizontal (Huxel et al., 2008; Turkel et al., 1981; Werner et al., 2007), it is not surprising that all subjects in the current cohort described internal rotation strengthening being focused upon in their rehabilitation program. However, our level of deficit was still higher than that recommended for return to sport. Specifically for shoulders, a deficit of < 10% for external rotation and nil deficit for internal rotation is accepted as the clearance criteria for safe return to sports following shoulder injury (Wilk et al., 2020; Wilson et al., 2020). This is less specific than Thomee et al (2012) where clearance criteria for strength deficits at the knee delineates contact and competitive sport from non-contact recreational sport. In respect of other studies, our deficit of 14% was like isokinetic deficits of 17% reported by Edouard et al., (2012) at six months post Latarjet surgery but higher that the 8% deficit at nine months reported by Amako et al. (2017). More recently, Yildiz et al. (2022) reported only 6% internal rotation strength deficits at six months after anterior stabilisation surgery.

Several factors might be involved in the degree of weakness observed. These include disuse leading to decreased muscle cross-sectional area (Ishikawa et al., 2023) and possibly arthrogenic inhibition (Pietrosimone et al., 2022; Rice & McNair, 2010). In respect of the latter, joint effusion together with glenohumeral ligamentous and capsular laxity may be present following injuries and re-injury. In the lower limb, deficits in strength remain despite surgery to reduce joint laxity (Mattacola et al., 2002; Nomura et al., 2015; Schmitt et al., 2015). Irrespective of the contributing factors, our findings highlight that some individuals may require more intensive strengthening for internal and external rotators post-surgery. This thought is supported by Gottlieb & Springer, (2021) who reported an association between strength levels and perceived function.

5.4 Force appreciation across limbs

The interaction between the static and dynamic stabilising structures at the shoulder is mediated by the sensorimotor system, and neuromuscular control is important to dynamic stability at the glenohumeral joint. Based upon previous research concerning joint position sense at the shoulder joint (Lephart et al., 1994; Lephart & Jari, 2002; Pötzl et al., 2004; Rokito et al., 2010; Zuckerman et al., 2003) and force appreciation research at the knee and ankle joint (Arnold & Docherty, 2006; Docherty & Arnold, 2008; Perraton et al., 2013, 2017; Telianidis et al., 2014; Ward et al., 2019) it was hypothesized that force appreciation might also be impaired at the shoulder following injury and such changes might remain apparent even after surgery to stabilise the joint.

With respect to our methods, force accuracy and steadiness were examined using a protocol with established reliability (Dover & Powers, 2003). Based upon pilot work a submaximal target force of 35% MVC was used, as this level has been shown to be typical of that applied in many shoulder tasks of function (Bandholm et al., 2006; Benze et al., 2009; Saccol et al., 2014; Zanca et al., 2013).

A significant deficit in force steadiness was observed for external rotators at the affected shoulder (5.5%) compared to the unaffected shoulder (4.6%). The SD values for the affected shoulder were higher than those reported by Saccol et al. (2014) for athletes with anterior instability (SD = 4.4%) and with SLAP lesion (SD = 4.3%). The SD values of the unaffected shoulder in our cohort were slightly higher than those of the healthy athletes (SD = 4%) reported by Saccol et al., 2014. While being statistically significant (<0.05) an important point to consider is whether our difference in force steadiness across limbs (0.9%) is of clinical relevance. It seems doubtful, as most clinicians would not alter their current rehabilitation program to remedy such a deficit. Similarly, an even smaller difference (0.3%) was also statistically significant steadiness for the internal rotators. Again, it could be argued that this difference is inconsequential, and unlikely to be important in performance of the joint in various functional tasks. The level of internal rotator steadiness (SD = 3%) that was observed was very similar to that reported by Saccol et al., 2014 (SD = 3.5%) as reported above.

Understanding the exact mechanisms that could have contributed to this small but significant result concerning the external rotators is beyond the scope of the current study, but we hypothesise that the following factors could have contributed to it. It seems most likely that the rehabilitation program exercises could play a role. Subjective discussion with each of our participants indicated exercise focused on strengthening, range of motion, neuromuscular control and sports specific tasks was undertaken by all participants, albeit with different intensities and durations over the first six months post-surgery. Previous research has reported that force steadiness can be improved with strengthening exercises (Hortobágyi. et al., 2001; Laidlaw et al., 1999; Vila-Chã & Falla, 2016), practising functional tasks (Marmon, Gould, et al., 2011) and visuomotor force-control training (Chung-Hoon et al., 2015; Magni et al., 2021; Wang et al., 2022). Of note, an association between force steadiness during hand tasks and functional tests was observed by Pascoe et al. (2011). Additionally, concerning training, Gould et al. (2011) reported that practicing a functional task such as the 'Grooved Pegboard' test contributed to improvement in force steadiness of index finger abduction steadiness. Furthermore, strength training at the knee in healthy young men was found to improve force steadiness during isometric contraction at a submaximal force (30% MVC) (Vila-Chã & Falla, 2016). Relatedly, recent work by Wang et al. (2022) showed that visuomotor force-control/ force appreciation training of hand muscles over eight days led to significant improvements in force accuracy over the first two days of training. These authors (Wang et al., 2022) also reported that this type of training induced cortical changes in the left sensorimotor cortex and supplementary motor areas, which are concerned with motor control. Based on evidence from the various studies mentioned here, it appears that different forms of training can improve force steadiness and force accuracy.

It is thought that the effect of strengthening exercises on force steadiness is through its influence on motor unit behaviour (Kornatz et al., 2005; Moritz et al., 2005; A. M. Taylor et al., 2003; Vila-Chã & Falla, 2016). Some authors (Kornatz et al., 2005; Moritz et al., 2005; Vila-Chã & Falla, 2016) have observed an association between decreased motor unit discharge rate variability and improvement in force steadiness. Taylor et al. (2003) identified the factors that contributed to steadiness in the upper limb at the hand. These were related to organisation of the motor-unit pool, motor unit recruitment and discharge rate modulation and the activation pattern of the motor units. Their research highlighted that rather than a single mechanism, the interaction of the aforementioned factors is more likely to contribute to force steadiness during isometric contractions at various force levels. Another factor concerning muscle activation, that might also be involved is altered coactivation of internal/external rotators. The coactivation of these muscles is thought to be important to stability of the head of humerus within the glenoid fossa (David et al., 2000; Myers et al., 2004). Relatedly, decreased force steadiness accompanied with increased hamstring activation during isometric quadriceps force matching was reported in individuals with ACLR (Perraton et al., 2017; Rice et al., 2021).

Worthy of consideration is that surgical intervention could lead to improvements in force appreciation. Regarding this point, at the shoulder joint, methods of surgical intervention for anterior stabilisation in the current cohort involve re-tensioning of capsuloligamentous structures at times with an inferior capsular shift. This restoration of capsular tension has been suggested to restore joint position sense at 6 to 12 months post-surgery (Lephart et al., 1994; Zuckerman et al., 2003). The mechanoreceptors in the joint capsule and ligaments contribute to force sense (Proske & Gandevia, 2012), and it is possible that anterior stabilisation surgery improved the afferent feedback from the mechanoreceptors in the anterior capsule.

Regarding force accuracy of internal and external rotators, there was no significant difference between the affected and unaffected shoulders. At the shoulder, Maenhout et al. (2012), has examined force accuracy in these muscles in patients with rotator cuff tendinopathy, and did not find any significant difference in absolute error between the affected and unaffected shoulders or across healthy controls. In additional to peripheral structures and their related central pathways mentioned previously (section 2.4.2.1 page 12-13, section 2.4.4 page 16-17), accuracy is also influenced considerably by vision. Limonta et al. (2015) showed that errors in force matching increased at a submaximal force level (20%MVC) when visual feedback was removed. Transfer of sensory information and subsequent integration in the cortical and subcortical centres allows adjustment of force production and correction of errors during visuo-motor force matching tasks but may cause delays in motor output required for error correction (Limonta et al., 2015; Vaillancourt & Russell, 2002). Vaillancourt & Russell, (2002) commented that force error information processing by visuomotor areas is stored in a short-term memory and after every one second interval an error correction signal is computed. Future research might investigate the impact of absence of visual feedback on force accuracy in individuals with shoulder stabilisation surgery.

Regarding the temporal measure, from torque rise to point of steadiness, there was no significant difference across limbs for internal and external rotators. Similar results were reported in (Benze et al., 2009) for a shoulder abduction task and (Zanca et al., 2013) for internal and external rotation force matching task. In the current study the mean time to steadiness of internal and external rotators varied from 0.75 to 0.85 and 1.25 to 1.54 seconds respectively. These times were shorter than those of Zanca et al. (2013) where times for external rotators varied from 2.28 to 2.41 and for internal rotators from 2.61 to 3.01. Requiring participants to generate force as fast as possible provided a dual task scenario, that demanded greater force control in the initial stage of the test. This instruction was also included as piloting had shown that without its inclusion participants often took between 5-10 seconds gradually approaching the 35%

target line tentatively. This could be due to a speed-accuracy ‘trade off’ strategy (Li et al., 2018; Peng et al., 2017).

5.5 The relationship between force appreciation and function

Kendall’s tau correlation coefficients showed that those individuals with higher LSIs for force accuracy in external rotators had higher perceived function, as measured by the WOSI. Similarly significant associations were observed for force accuracy and force steadiness LSIs of the internal rotators with perceived function as measured by the ROWE. This partially supports our hypothesis that there would be a relationship between force appreciated and perceived function.

An important point is that while the WOSI and the ROWE fall under the umbrella of perceived function and have previously been shown to be moderately correlated with each other (Kirkley et al., 1998; Park et al., 2018), they are different in respect to the key factors that they are thought to represent. The WOSI is focused upon physical symptoms, lifestyle and emotional aspects of perceived function while the ROWE is thought to more represent physical symptoms. Since both questionnaires brought forth a similar significant correlation provides additional strength for our findings. Though again it should be recognised that although statistically significant, their contribution to total variance related to function can be regarded as small (10 - 12%) and may indeed not be clinically relevant. It seems most likely that force appreciation might play a small role amongst several other variables that contribute to our perception of function. The limited number of participants in the current work precluded a modelling approach that would likely involve a combination of biomechanical, physiological and psychological variables. Nevertheless, notable researchers in the neuromuscular area (Myers et al., 2006; Myers & Lephart, 2000) have commented that less accurate force production could affect the neuromuscular control at the shoulder affecting everyday functional activities. Of note too, associations between force appreciation measures and perceived function have been reported in ACLR research (Perraton et al., 2017).

More recently, an association between WOSI and external rotation strength difference between limbs in surgically stabilised shoulders was reported (Gottlieb & Springer, 2021)**.** Furthermore, a pilot study by (D’Alessandro et al., 2021) found significant negative associations between WOSI and LSIs for peak force and rate of force development in the Athletic Shoulder test (ASH); which involves isometric testing with the arm in three different positions. Thus, it appears that the WOSI score can be associated with different muscle related performance measures.

Regarding our physical performance test, we found no significant relationship between the BABER test LSI and force accuracy and steadiness variables. We chose the BABER test because it engaged muscles at lower force levels and had elements of motor control/coordination which were less present in the line hop and the side-hold rotation test. These latter two tests utilise maximal effort to generate as much power as possible over a minute, and hence are likely to engage larger motor units with type II fibres to a point where fatigue would be very apparent as anaerobic metabolism generates considerable waste products (eg: potassium, lactate, hydrogen ions) and subsequently contractile force capacity becomes disrupted (Green, 1994; Hopkins et al., 2001). Thus, they are quite different to the force appreciation tasks that we utilised. Perhaps other neuromuscular variables more specific to power-based muscle performance are more likely to be associated with these tests. It is known that strength-based training leads to improvement in force appreciation measures in particular force steadiness (Hortobágyi. et al., 2001; Vila-Chã & Falla, 2016). Hence it was hypothesized that there could be a correlation between the performance tests and force appreciation measures.

5.6 Limitations of this study

Inclusion of control group would have been ideal, but due to issues previously described concerning Covid-19 lockdowns and individual’s apprehension of coming to the university even when these were not in place was unable to be controlled for. However, research on force appreciation at the shoulder (Benze et al., 2009) indicated that there was no significant difference between the unaffected shoulder and control group. Hence a comparison of force appreciation between the affected and unaffected side was in part justified and provided us with meaningful information regarding difference across limbs for various measures. A second related limitation was that during recruitment we had to extend the scope of surgical procedures to include all types of anterior stabilisation surgeries. This was also done to facilitate participant recruitment which was affected by the Covid-19 pandemic. Based on the small numbers, it was not possible to perform sub-group analyses across surgical procedures. However, considering that the timeframe from surgery was 6-12 months (and all subjects had been cleared for sport), and based on previous research (Bottoni et al., 2006; Mohtadi et al., 2014) and discussions with surgeons, it was thought justified to include all types of surgeries in the current study, and it was unlikely that they would affect the results notably.

The testing protocol involved use of isokinetic dynamometer. The isometric force matching was performed with the arm in 90^{o} abduction in scapular plane with shoulder externally rotated. The reliability for force appreciation testing in this position is established and this replicated the position which challenges the anterior stabilising mechanism at the shoulder (Saccol et al., 2014). The external rotators were placed in a shortened position during isometric force matching. This angle of testing changes muscle length and could influence force steadiness and accuracy (Cafarelli & Bigland-Ritchie, 1979; Dover & Powers, 2003; Krishnan et al., 2011; Li et al., 2020; Weerakkody et al., 2003). We acknowledge that effect of shoulder external rotator muscle length on force appreciation was previously examined, and this could have influenced the results of the current study.

Whilst the results for force steadiness examined with isometric force matching at the shoulder were statistically significant the difference was small, and its clinical relevance is questionable. Perhaps an investigation of force appreciation using a force modulation protocol that involved concentric and eccentric muscle work could have provided with further insights. However, this would have increased the duration of testing session over 1.5 hours.

We did not measure joint position sense or muscle activation with EMG. These tests would have added to our ability to explore potential mechanisms. However, combining such methods to assess other neuromuscular and proprioception constructs would have lengthened the duration of testing notably and thereby its feasibility.

Finally, we did not include objective measurement of joint laxity. Excess shoulder joint laxity may influence force appreciation at the shoulder through alterations in joint biomechanics and/or neuromuscular activation (via afferent and efferent pathways). Our study was not designed to examine whether there was change in this measure following shoulder stabilisation surgery.

5.7 Summary and Conclusions

This study had two main objectives. Firstly, the force appreciation between the affected (operated) and unaffected (not operated) shoulders was examined in individuals who had anterior stabilisation surgery and were at 6-12 months from time of surgery. Force steadiness error in external rotators was significantly greater in the affected shoulder. Internal rotator force steadiness error was significantly increased ($p<0.05$) on the unaffected side but by a meagre amount. These findings were novel but considering the small differences across limbs, they do not provide impetus to change current clinical practice. However, they provide a starting point upon which further research that targets different measures related to force appreciation could be undertaken.

Although not a primary focus, strength testing of shoulder internal and external rotators revealed significant deficits across limbs (14% & 23% respectively) at a time point when participants had received clearance to return to sports. These results were of concern and highlighted the need for strength testing at various time points to identify individuals who may require additional exercise to remedy such deficits, and perhaps allow a safer return to sports.

The second objective was to assess the relationship between perceived function, a physical performance test and the difference across limbs (LSI) for force appreciation variables was investigated. Kendall tau correlation coefficients showed that those individuals with higher LSIs for force accuracy in external rotators had higher perceived function, as measured by the WOSI. Similar significant associations were observed for force accuracy and force steadiness LSIs of the internal rotators with perceived function as measured by the ROWE. In regard to associations, the findings highlight that improved force appreciation is associated with improved perceived function, but individually, the variables tested contribute to a small proportion of change in perceived function. It is likely that a larger study allowing multiple variables to be incorporated within a model would be a valuable next step.

5.8 Clinical implications

This study provides initial evidence that significant differences in force accuracy and steadiness are present at the affected shoulder in a cohort with anterior stabilisation surgery. However, the difference across limbs being minimal does not provide the drive to change clinical practice by including force appreciation type of exercises in rehabilitation. As mentioned previously further research is required to examine force appreciation with protocols using concentric or eccentric muscle work to expand our understanding about force appreciation in shoulder after anterior stabilisation surgery.

5.9 Future Research

Several key areas for future research have been identified.

1) Examining force appreciation at different angles of rotation at the shoulder would be beneficial to understanding the effect of change in muscle length of internal and external rotators on force appreciation. This will also be useful to standardise the protocol for force appreciation testing of these muscles.

2) The present study investigated force appreciation using an isometric force matching protocol. Further examination using a force modulation task is warranted to get more comprehensive understanding of force appreciation during dynamic tasks. Also, examination of force appreciation in individuals with anterior stabilisation surgery without visual feedback, perhaps even under fatigue would give further understanding as how this might influence neuromuscular control in activities/sports that induces muscle fatigue or where individuals have no visuomotor reference of force.

3) Examination of force appreciation before and after surgery is warranted to understand whether it is influenced by surgery and rehabilitation. Also including equal proportion of participants with Latarjet and other anterior stabilisation surgeries could allow us to compare whether type of surgery influences force appreciation before and after surgery.

In the context of influence of training methods on force appreciation, future studies could examine the effect of different types of strengthening exercises/ visuomotor force control tasks on force appreciation at the shoulder. A study like this may provide new insights that could be utilised in the rehabilitation programme.

References

Abboud, J. A., & Soslowsky, L. J. (2002). Interplay of the static and dynamic restraints in glenohumeral instability. *Clinical Orthopaedics and Related Research*, *400*, 48–57.

Adamo, D. E., Scotland, S., & Martin, B. J. (2012). Asymmetry in grasp force matching and sense of effort. *Experimental Brain Research*, *217*(2), 273–285. doi:10.1007/s00221-011-2991-6

Arnold, B., & Docherty, C. (2006). Low-load eversion force sense, self-reported ankle instability, and frequency of giving way. *Journal of Athletic Training*, *41*(3), 233–238.

Bandholm, T., Rasmussen, L., Aagaard, P., Diederichsen, L., & Jensen, B. R. (2008). Effects of experimental muscle pain on shoulder-abduction force steadiness and muscle activity in healthy subjects. *European Journal of Applied Physiology*, *102*(6), 643–650. doi:10.1007/s00421-007-0642-1

Bandholm, T., Rasmussen, L., Aagaard, P., Jensen, B. R., & Diederichsen, L. (2006). Force steadiness, muscle activity, and maximal muscle strength in subjects with subacromial impingement syndrome. *Muscle and Nerve*, *34*(5), 631–639. doi:10.1002/mus.20636

Bandholm, T., Rose, M. H., Sonne-Holm, S., & Jensen, B. R. (2008). Assessment of torque-steadiness reliability at the ankle level in healthy young subjects: Implications for cerebral palsy. *European Journal of Applied Physiology*, *104*(4), 609–615. doi:10.1007/s00421-008-0808-5

Bassett, R. W., Browne, A. 0, Morrey, B. F., & An, K. N. (1990). Glenohumeral muscle force and moment mechanics in a position of shoulder instability. *Journal of Biomechanics*, *23*(5), 405–415. doi:10.1016/0021-9290(90)90295-E

Baweja, H. S., Patel, B. K., Martinkewiz, J. D., Vu, J., & Christou, E. A. (2009). Removal of visual feedback alters muscle activity and reduces force variability during constant isometric contractions. *Experimental Brain Research*, *197*(1), 35–47. doi:10.1007/s00221-009-1883-5

Benze, B. G., Asso, N. A., de Fátima S. T., de Oliveira, A. B., Avila, M. A., & Camargo, P. R. (2009). Shoulder abduction torque steadiness is preserved in subacromial impingement syndrome. *European Journal of Applied Physiology*, *106*(3), 381–387. doi:10.1007/s00421-009-1030-9

Bohu, Y., Abadie, P., van Rooij, F., Nover, L., Kany, J., Colotte, P., Kelberine, F., Fontes, D., Thelu, C. E., Sanchez, M., Berhouet, J., & Hardy, A. (2021). Latarjet procedure enables 73% to return to play within 8 months depending on preoperative SIRSI and Rowe scores. *Knee Surgery, Sports Traumatology, Arthroscopy*, *29*(8), 2606–2615. doi:10.1007/s00167-021-06475-1

Boileau, P., Mercier, N., Roussanne, Y., Thélu, C. É., & Old, J. (2010). Arthroscopic Bankart-Bristow-Latarjet procedure: The development and early results of a safe and reproducible technique. *Arthroscopy: Journal of Arthroscopic and Related Surgery*, *26*(11), 1434–1450. doi:10.1016/j.arthro.2010.07.011

Boline, J., & Ashe, J. (2005). On the relations between single cell activity in the motor cortex and the direction and magnitude of three-dimensional dynamic isometric force. *Experimental Brain Research*, *167*(2), 148–159. doi:10.1007/s00221-005-0016-z

Borms, D., & Cools, A. (2018). Upper-Extremity Functional Performance Tests: Reference Values for Overhead Athletes. *International Journal of Sports Medicine*, *39*(6), 433–441. doi:10.1055/a-0573-1388

Borms, D., Maenhout, A., & Cools, A. M. (2016). Upper quadrant field tests and isokinetic upper limb strength in overhead athletes. *Journal of Athletic Training*, *51*(10), 789–796. doi:10.4085/1062-6050-51.12.06

Bosco, G., & Poppele, R. E. (2001). Proprioception from a spinocerebellar perspective. *Physiological Reviews*, *81*(2), 539–568.

Bottoni, C. R., Smith, E. L., Berkowitz, M. J., Towle, R. B., & Moore, J. H. (2006). Arthroscopic versus open shoulder stabilization for recurrent anterior instability: A prospective randomized clinical trial. *American Journal of Sports Medicine*, *34*(11), 1730–1737. doi:10.1177/0363546506288239

Bouliane, M., Saliken, D., Beaupre, L. A., Silveira, A., Saraswat, M. K., Sheps, D. M., Silveira, ν A, Associate, R., & Saraswat, ν M K. (2014). Evaluation of the Instability Severity Index Score and the Western Ontario Shoulder Instability Index as predictors of failure following arthroscopic Bankart repair. *Bone Joint J*, 96–1688. doi:10.1302/0301-620X.96B12

Brereton, H. (2007). *Acuity of force appreciation in the osteoarthritic knee joint* [Masters Theses, Auckland University of Technology]. http://hdl.handle.net/10292/301

Brink, E., Jankowska, E., McCrea, D. A., & Skoog, B. (1983). Inhibitory interactions between interneurones in reflex pathways from group Ia and group Ib afferents in the cat. *The Journal of Physiology*, *343*(1), 361–373. doi:10.1113/jphysiol.1983.sp014897

Brooks, J., Allen, T. J., & Proske, U. (2013). The senses of force and heaviness at the human elbow joint. *Experimental Brain Research*, *226*(4), 617–629. doi:10.1007/s00221-013-3476-6

Brophy, R. H., & Marx, R. G. (2005). Osteoarthritis following shoulder instability. *Clinics in Sports Medicine* 24 (1), 47–56. doi:10.1016/j.csm.2004.08.010

Burke, D., Hagbarth, K. E., & Löfstedt, L. (1978). Muscle spindle activity in man during shortening and lengthening contractions. *The Journal of Physiology*, *277*(1), 131–142. doi:10.1113/jphysiol.1978.sp012265

Cafarelli, E. (1982). Peripheral contributions to the perception of effort. *Medicine and Science in Sports and Exercise*, *14*(5), 382–389.

Cafarelli, E., & Bigland-Ritchie, B. (1979). Sensation of static force in muscles of different length. *Experimental Neurology*, *65*, 511–525. doi:10.1016/0014-4886(79)90040-2

Cain, W. S., & Stevens, J. C. (1971). Effort in sustained and phasic handgrip contractions. *The American Journal of Psychology*, 84 (1), 52-65. doi:10.2307/1421224.

Caubère, A., Lami, D., Boileau, P., Parratte, S., Ollivier, M., & Argenson, J. N. (2017). Is the subscapularis normal after the open Latarjet procedure? An isokinetic and magnetic resonance imaging evaluation. *Journal of Shoulder and Elbow Surgery*, *26*(10), 1775–1781. doi:10.1016/j.jse.2017.03.034

Chung-Hoon, K., Tracy, B. L., Marcus, R., Dibble, L., Burgess, P., & Lastayo, P. C. (2015). Effects of practice on variability of muscle force. *Perceptual and Motor Skills*, *120*(2), 475–490. doi:10.2466/26.PMS.120v12x4

Cordasco, F. A., Lin, B., Heller, M., Asaro, L. A., Ling, D., & Calcei, J. G. (2020). Arthroscopic shoulder stabilization in the young athlete: return to sport and revision stabilization rates. *Journal of Shoulder and Elbow Surgery*, *29*(5), 946–953. doi:10.1016/j.jse.2019.09.033

Coren, S. (2003). Sensation and Perception. In D. Freedheim, I. Weiner (Eds.), Handbook of psychology: Volume 1, history of psychology (pp.85-108). John Wiley & Sons Inc.

Coyle, M., Jaggi, A., Weatherburn, L., Daniell, H., & Chester, R. (2022). Post-operative rehabilitation following traumatic anterior shoulder dislocation: A systematic scoping review. *Shoulder and Elbow*, 0(0), 1-12. doi:10.1177/17585732221089636

Crago, P. E., Houk, J. C., & Rymer, W. Z. (1982). Sampling of total muscle force by tendon organs. *Journal of Neurophysiology*, *47*(6), 1069-1083. doi:10.1152/jn.1982.47.6.1069

Cunningham, G., Zanchi, D., Emmert, K., Kopel, R., Van De Ville, D., Lädermann, A., Haller, S., & Hoffmeyer, P. (2015). Neural correlates of clinical scores in patients with anterior shoulder apprehension. *Medicine Science Sports Exercise*, *47*(12), 2612–2620. doi:10.1249/MSS.0000000000000726

D'Alessandro, P., Ebert, J., & Edwards, P. (2021). Associations between patient-reported scores, strength and physical performance tests following shoulder stabilisation surgery. *Journal of Science and Medicine in Sport*, *24* (1), S33. doi:10.1016/j.jsams.2021.09.087

David, G., Magarey, M. E., Jones, M. A., Dvir, Z., Turker, K. S., & Sharpe, M. (2000). EMG and strength correlates of selected shoulder muscles during rotations of the glenohumeral joint. *Clinical Biomechanics*, *15*(2), 95–102. doi:10.1016/S0268-0033(99)00052-2

De Graaf, J. B., Galléa, C., Pailhous, J., Anton, Jean. L., Roth, M., & Bonnard, M. (2004). Awareness of muscular force during movement production: an fMRI study. *NeuroImage*, 1357–1367. doi:10.1016/j.neuroimage.2003.11.009ï

Dekker, T. J., Peebles, L. A., Bernhardson, A. S., Golijanin, P., Di Giacomo, G., Hackett, T. R., & Provencher, M. T. (2021). Limited predictive value of the instability severity index score: evaluation of 217 consecutive cases of recurrent anterior shoulder instability. *Arthroscopy: Journal of Arthroscopic and Related Surgery*, *37*(5), 1381–1391. doi:10.1016/j.arthro.2020.12.185

Docherty, C. L., & Arnold, B. L. (2008). Force sense deficits in functionally unstable ankles. *Journal of Orthopaedic Research*, *26*(11), 1489–1493. doi:10.1002/jor.20682

Dodson, C. C., & Cordasco, F. A. (2008). Anterior glenohumeral joint dislocations. *Orthopedic Clinics of North America*, Vol. 39 (4), 507–518. doi:10.1016/j.ocl.2008.06.001

Donohue, M. A., Brelin, A. M., & LeClere, L. E. (2016). Management of First-Time Shoulder Dislocation in the Contact Athlete. *Operative Techniques in Sports Medicine*, *24*(4), 236–241. doi:10.1053/j.otsm.2016.09.001

Dover, G., & Powers, M. E. (2003). Reliability of joint position sense and force-reproduction measures during internal and external rotation of the shoulder. *Journal of Athletic Training*.

Dumont, G. D., Russell, R. D., & Robertson, W. J. (2011). Anterior shoulder instability: A review of pathoanatomy, diagnosis and treatment. *Current Reviews in Musculoskeletal Medicine*, 4 (4), 200–207. doi:10.1007/s12178-011-9092-9

Ebert, J. R., Edwards, P., Yi, L., Joss, B., Ackland, T., Carey-Smith, R., Buelow, J. U., & Hewitt, B. (2018). Strength and functional symmetry is associated with post-operative rehabilitation in patients following anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy*, *26*(8), 2353–2361. doi:10.1007/s00167-017-4712-6

Edouard, P., Bankolé, C., Calmels, P., Beguin, L., & Degache, F. (2013). Isokinetic rotator muscles fatigue in glenohumeral joint instability before and after Latarjet surgery A pilot prospective study. *Scandinavian Journal of Medicine and Science in Sports*, *23*(2). doi:10.1111/sms.12011

Edouard, P., Beguin, L., Degache, F., Fayolle-Minon, I., Farizon, F., & Calmels, P. (2012). Recovery of rotators strength after latarjet surgery. *International Journal of Sports Medicine*, *33*(9), 749–755. doi:10.1055/s-0031-1298001

Edouard, P., Degache, F., Beguin, L., Samozino, P., Gresta, G., Fayolle-Minon, I., Farizon, F., & Calmels, P. (2011). Rotator cuff strength in recurrent anterior shoulder instability. *Journal of Bone and Joint Surgery*, *93*(8), 759–765. doi:10.2106/JBJS.I.01791

Eiger, B., Errebo, M., Straszek, C. L., & Vaegter, H. B. (2023). Less is more: Reliability and measurement error for three versions of the Tampa Scale of Kinesiophobia (TSK-11, TSK-13, and TSK-17) in patients with high-impact chronic pain. *Scandinavian Journal of Pain*, *23*(1), 217–224. doi:10.1515/sjpain-2021-0200

Elsenbeck, M. J., & Dickens, J. F. (2017). Return to sports after shoulder stabilization surgery for anterior shoulder instability. *Current Reviews in Musculoskeletal Medicine*, *10*(4), 491–498. doi:10.1007/s12178-017-9440-5

Enoka, R. M., & Farina, D. (2021). Force steadiness: From motor units to voluntary actions. *Physiology*, *36*(2), 114–130. doi:10.1152/physiol.00027.2020

Eshoj, H., Rasmussen, S., Frich, L. H., Hvass, I., Christensen, R., Jensen, S. L., Søndergaard, J., Søgaard, K., & Juul-Kristensen, B. (2017). A neuromuscular exercise programme versus standard care for patients with traumatic anterior shoulder instability: Study protocol for a randomised controlled trial (the SINEX study). *Trials*, *18*(1), 1–10. doi:10.1186/s13063-017-1830-x

Eshoj, H., Rasmussen, S., Frich, L. H., Jensen, S. L., Søgaard, K., & Juul-Kristensen, B. (2019). Patients with non-operated traumatic primary or recurrent anterior shoulder dislocation have equally poor self-reported and measured shoulder function: A cross-sectional study. *BMC Musculoskeletal Disorders*, *20*(1), 1-9. doi:10.1186/s12891-019-2444-0

Espindola, B. M., Ruschel, C., Fontana, H. B., Santos, D. P. dos, Noronha, M. A., & Haupenthal, A. (2011). Relative error analysis during reproduction of isometric force of knee extensors in young adults. *Portuguese Journal of Sport Sciences*, 11 (1), 871-874.

Floegel, M., Steinmetz, S., Dimova, V., Kell, C. A., & Birklein, F. (2022). Aberrant sensorimotor coupling and movement planning in Complex Regional Pain Syndrome. *Pain*, 1–11. doi:10.1097/j.pain.0000000000002805

Franklin, D. W., & Wolpert, D. M. (2011). Computational mechanisms of sensorimotor control. *Neuron*, *72*(3), 425–442. doi:10.1016/j.neuron.2011.10.006

Fremerey, R., Bosch, U., Lobenhoffer, P., & Wippermann, B. (2006). Joint position awareness and sports activity after capsulolabral reconstruction in the overhead athlete. *International Journal of Sports Medicine*, *27*(8), 648–652. doi:10.1055/s-2005-865815

French, D. J., France, C. R., Vigneau, F., French, J. A., & Evans, R. T. (2007). Fear of movement/(re)injury in chronic pain: A psychometric assessment of the original English version of the Tampa scale for kinesiophobia (TSK). *Pain*, *127*(1–2), 42–51. doi:10.1016/j.pain.2006.07.016

Galvin, J. W., Ernat, J. J., Waterman, B. R., Stadecker, M. J., & Parada, S. A. (2017). The epidemiology and natural history of anterior shoulder instability. *Current Reviews in Musculoskeletal Medicine*, 10, 411-424. doi:10.1007/s12178-017-9432-5

Gandevia, S. C. (1998). Neural control in human muscle fatigue: Changes in muscle afferents, moto neurones and moto cortical drive. *Acta Physiologica Scandinavica*, *162*(3), 275–283. doi:10.1046/j.1365-201X.1998.0299f.x

Gandevia, S. C., & Kilbreath, S. L. (1990). Accuracy of weight estimation for weights lifted by proximal and distal muscles of the human upper limb. *The Journal of Physiology*, *423*(1), 299–310. doi:10.1113/jphysiol.1990.sp018023

Gandevia, S. C., & McCloskey, D. I. (1977). Changes in motor commands, as shown by changes in perceived heaviness, during partial curarization and peripheral anaesthesia in man. *The Journal of Physiology*, *272*(3), 673–689. doi:10.1113/jphysiol.1977.sp012066

Gandevia, S. C., McCloskey, D. I., & Potter, E. K. (1980). Alterations in perceived heaviness during digital anaesthesia. *The Journal of Physiology*, *306*(1), 365–375. doi:10.1113/jphysiol.1980.sp013402

Gaunt, B. W., Shaffer, M. A., Sauers, E. L., Michener, L. A., Mccluskey, G. M., & Thigpen, C. A. (2010). The American Society of Shoulder and Elbow Therapists' consensus rehabilitation guideline for arthroscopic anterior capsulolabral repair of the shoulder. *Journal of Orthopaedic and Sports Physical Therapy*, *40*(3), 155–168. doi:10.2519/jospt.2010.3186

Georgopoulos, A. P., Ashe, J., Smyrnis, N., & Taira, M. (1992). Motor cortex and coding of force. *Science*, *256*(5064), 1692–1695. doi:10.1126/science.256.5064.1692

Gerometta, A., Klouche, S., Herman, S., Lefevre, N., & Bohu, Y. (2018). The Shoulder Instability-Return to Sport after Injury (SIRSI): a valid and reproducible scale to quantify psychological readiness to return to sport after traumatic shoulder instability. *Knee Surgery, Sports Traumatology, Arthroscopy*, *26*(1), 203–211. doi:10.1007/s00167-017-4645-0

Gerometta, A., Rosso, C., Klouche, S., & Hardy, P. (2016). Arthroscopic Bankart shoulder stabilization in athletes: return to sports and functional outcomes. *Knee Surgery, Sports Traumatology, Arthroscopy*, *24*(6), 1877–1883. doi:10.1007/s00167-014-2984-7

Gibson, J. C. (2004). (iii) Rehabilitation after shoulder instability surgery. *Current Orthopaedics*, *18*(3), 197–209. doi:10.1016/j.cuor.2004.03.003

Gilman, S. (2002). Joint position sense and vibration sense: Anatomical organisation and assessment. *Journal of Neurology Neurosurgery and Psychiatry*, 73 (5), 473–477. doi:10.1136/jnnp.73.5.473

Gohlke, F., Essigkrug, B., & Schmitz, F. (1994). The pattern of the collagen fiber bundles of the capsule of the glenohumeral joint. *Journal of Shoulder and Elbow Surgery*, *3*(3), 111–128. doi:10.1016/S1058-2746(09)80090-6

Goodwin, G. M., Mccloskey, D. I., & Matthews, P. B. C. (1972). The contribution of muscle afferents to kinaesthesia shown by vibration induced illusions of movement and by the effects of paralysing joint afferents. *Brain,* 95, 705-748.

Gottlieb, U., & Springer, S. (2021). The relationship between fear avoidance beliefs, muscle strength, and short-term disability after surgical repair of shoulder instability. *Journal of Sport Rehabilitation*, *30*(7), 973–980. doi:10.1123/jsr.2020-0035

Green, S. (1994). A definition and systems view of anaerobic capacity. *European Journal of Applied Physiology and Occupational Physiology*, *69*(2), 168–173. doi:10.1007/BF00609411

Gregory, J. E., & Proske, U. (1979). The responses of Golgi tendon organs to stimulation of different combinations of motor units. *The Journal of Physiology*, *295*(1), 251–262. doi:10.1113/jphysiol.1979.sp012966

Hagen, M., Lemke, M., & Lahner, M. (2018). Deficits in subtalar pronation and supination proprioception in subjects with chronic ankle instability. *Human Movement Science*, *57*, 324–331. doi:10.1016/j.humov.2017.09.010

Harada, Y., Iwahori, Y., Kajita, Y., Takahashi, R., Yokoya, S., Sumimoto, Y., Deie, M., & Adachi, N. (2022). Return to sports after arthroscopic bankart repair on the dominant shoulder in overhead athletes. *Journal of Orthopaedic Science*, *27*(6), 1240–1245. doi:10.1016/j.jos.2021.07.014

Harris, P. A., Taylor, R., Minor, B. L., Elliott, V., Fernandez, M., O'Neal, L., McLeod, L., Delacqua, G., Delacqua, F., Kirby, J., & Duda, S. N. (2019). The REDCap consortium: Building an international community of software platform partners. In *Journal of Biomedical Informatics*, 95,103208. doi:10.1016/j.jbi.2019.103208

Harris, P. A., Taylor, R., Thielke, R., Payne, J., Gonzalez, N., & Conde, J. G. (2009). Research electronic data capture (REDCap)-A metadata-driven methodology and workflow process for providing translational research informatics support. *Journal of Biomedical Informatics*, *42*(2), 377–381. doi:10.1016/j.jbi.2008.08.010

Hopkins, W. G., Schabort, E. J., & Hawley, J. A. (2001). Reliability of Power in Physical Performance Tests. *Sports Medicine*, *31*, 211–234.

Horcholle-Bossavit, G., Jami, L., Petit, J., Vejsada, R., & Zytnicki, D. (1988). Effects of muscle shortening on the responses of cat tendon organs to unfused contractions. *Journal of Neurophysiology* ,59 (5), 1510-1523. doi:10.1152/jn.1988.59.5.1510

Hortobágyi, T., Garry, J., Holbert, D., & Devita, P. (2004). Aberrations in the control of quadriceps muscle force in patients with knee osteoarthritis. *Arthritis Care & Research*, *51*(4), 562–569. doi:org/10.1002/art.20545

Hortobágyi., T., Tunnel., D., Moody., J., Beam., S., & Devita., P. (2001). Low- or high-intensity strength training partially restores impaired quadriceps force accuracy and steadiness in aged adults. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *56*(1), B38–B47. doi:10.1093/Gerona/56.1B38

Hou, W., Shen, S., Szameitat, A. J., Jiang, Y., Zheng, J., Van Loon, M., & Sterr, A. (2008). A behaviour study of the effects of visual feedback on fluctuating isometric force production with force tracking tasks "A behaviour study of the effects of visual feedback on fluctuating isometric force production with force tracking tasks." *International Journal of Biomedical Engineering and Technology*, *1*(4), 367–381. doi:10.1504/IJBET.2008.020067

Hurley, E. T., Davey, M. S., Montgomery, C., O'Doherty, R., Gaafar, M., Pauzenberger, L., & Mullett, H. (2021). Arthroscopic Bankart repair versus open latarjet for recurrent shoulder instability in athletes. *Orthopaedic Journal of Sports Medicine*, *9*(9), 1-6. doi:10.1177/23259671211023801

Hurley, E. T., Montgomery, C., Jamal, M. S., Shimozono, Y., Ali, Z., Pauzenberger, L., & Mullett, H. (2019). Return to play after the Latarjet procedure for anterior shoulder instability: a systematic review. *The American Journal of Sports Medicine*, *47*(12), 3002–3008. doi:10.1177/0363546519831005

Ishikawa, H., Smith, K. M., Wheelwright, J. C., Christensen, G. V., Henninger, H. B., Tashjian, R. Z., & Chalmers, P. N. (2023). Rotator cuff muscle imbalance associates with shoulder instability direction. *Journal of Shoulder and Elbow Surgery*, *32*(1), 33–40. doi:10.1016/j.jse.2022.06.022

Itoi, E., Newman, S. R., Kuechle, D. K., Morrey, B. F., An, K.-N., Kuechle, D. K., & Morrey, B. F. (1994). Dynamic anterior stabilisers of the shoulder with the arm in abduction. *The Journal of Bone and Joint Surgery*, *76*(5), 834–836. doi:10.1302/0301-620X.76B5.8083280

Itoigawa, Y., & Itoi, E. (2016). Anatomy of the capsulolabral complex and rotator interval related to glenohumeral instability. In *Knee Surgery, Sports Traumatology, Arthroscopy*, 24 (2),343–349. doi:10.1007/s00167-015-3892-1

Jackson, A. W., & Dishman, R. K. (2000). Perceived submaximal force production in young adult males and females. *Medicine and Science in Sports and Exercise,* 32(3), 448-451. doi:10.1097/00005768-200002000-00028

Jami, N. (1992). Golgi tendon organs in mammalian skeletal muscle: Functional properties and central actions. *Pysiological Reviews*, *72*(3), 623—666. doi:10.1152/physrev.1992.72.3.623

Jensen, K. U., Bongaerts, G., Bruhn, R., & Schneider, S. (2009). Not all Rowe scores are the same! Which Rowe score do you use? *Journal of Shoulder and Elbow Surgery*, *18*(4), 511–514. doi:10.1016/j.jse.2009.02.003

Jones. (2014). Measurement and analysis of sensory-motor performance: Tracking tasks. *Medical Devices and Human Engineering*, 31-1- 31-27.

Jones, E. G. (1972). The development of the “muscular sense” concept during the nineteenth century and the work of H. Charlton Bastian. *Journal of The History of Medicine and Allied Sciences*, *27*(3), 298–311. doi:10.1093/jhmas/XXVII.3.298

Jones, K. E., Wessberg, J., & Vallbo, Å. B. (2001). Directional tuning of human forearm muscle afferents during voluntary wrist movements. *Journal of Physiology*, *536*(2), 635–647. doi:10.1111/j.1469-7793.2001.0635c.xd

Jones, L. A. (1986). Perception of Force and Weight: theory and research. *Psychological Bulletin*, *100*(1), 29–42. doi:10.1037/0033-2909.100.1.29

Jones, L. A. (2003). Perceptual constancy and the perceived magnitude of muscle forces. *Experimental Brain Research*, *151*(2), 197–203. doi:10.1007/s00221-003-1434-4

Jones, L. A., & Hunter, I. W. (1983). Effect of Fatigue on Force Sensation. *Experimental Neurology*, *81*(3), 640–650. doi:10.1016/0014-4886(83)90332-1

Jones, L. A., & Piateski, E. (2006). Contribution of tactile feedback from the hand to the perception of force. *Experimental Brain Research*, *168*(1–2), 298–302. doi:10.1007/s00221-005-0259-8

Jones, L. A., & Tan, H. Z. (2013). Application of psychophysical techniques to haptic research. *IEEE Transactions on Haptics*, *6*(3), 268–284. doi:10.1109/TOH.2012.74

Juré, D., Blache, Y., Degot, M., Vigne, G., Nové-Josserand, L., Godenèche, A., Collotte, P., Franger, G., Borel, F., Rogowski, I., & Neyton, L. (2022). The S-

STARTS Test: Validation of a Composite Test for the Assessment of Readiness to Return to Sport After Shoulder Stabilization Surgery. *Sports Health*, *14*(2), 254–261. doi:10.1177/19417381211004107

Kalaska, J. F. (2009). From intention to action: Motor cortex and the control of reaching movements. *Advances in Experimental Medicine and Biology*, *629*, 139–178. doi:10.1007/978-0-387-77064-2_8

Kaufman, M. P., Longhurst, J. C., Rybicki, K. J., Wallach, J. H., & Mitchell, J. H. (2022). *Journal of Applied Physiology*, *55*(1), 105–112. doi:10.1152/jappl.1983.55.1.105

Keisker, B., Hepp-Reymond, M. C., Blickenstorfer, A., & Kollias, S. S. (2010). Differential representation of dynamic and static power grip force in the sensorimotor network. *European Journal of Neuroscience*, *31*(8), 1483–1491. doi:10.1111/j.1460-9568.2010.07172.x

Kemp, K. A. R., Sheps, D. M., Beaupre, L. A., Styles-Tripp, F., Luciak-Corea, C., & Balyk, R. (2012). An evaluation of the responsiveness and discriminant validity of shoulder questionnaires among patients receiving surgical correction of shoulder instability. *The Scientific World Journal*, *2012*. doi:10.1100/2012/410125

Kim, C. Y., Choi, J. D., & Kim, H. D. (2014). No correlation between joint position sense and force sense for measuring ankle proprioception in subjects with healthy and functional ankle instability. *Clinical Biomechanics*, *29*(9), 977–983. doi:10.1016/j.clinbiomech.2014.08.017

Kim, H. J., Kim, J. S., & Chung, C. K. (2023). Identification of cerebral cortices processing acceleration, velocity, and position during directional reaching movement with deep neural network and explainable AI. *NeuroImage*, *266*, 119783. doi:10.1016/j.neuroimage.2022.119783

Kirkley, A., Griffin, S., McLintock, H., & Ng, L. (1998). The development and evaluation of a disease-specific quality of life measurement tool for shoulder instability. *The American Journal of Sports Medicine*, *26*(6), 764–772. doi:10.1177/03635465980260060501

Komar, J., Seifert, L., & Thouvarecq, R. (2016). What variability tells us about motor expertise: Measurements and perspectives from a complex system approach. *Movement and Sports Sciences - Science & Motricite'*, *89*(3), 65–77. doi:10.1051/sm/2015020

Kornatz, K. W., Christou, E. A., & Enoka, R. M. (2005). Practice reduces motor unit discharge variability in a hand muscle and improves manual dexterity in old adults. *Journal of Applied Physiol*ogy, *98*, 2072–2080. doi:10.1152/japplphysiol.01149.2004.-A

Krishnan, C., Allen, E. J., & Williams, G. N. (2011). Effect of knee position on quadriceps muscle force steadiness and activation strategies. *Muscle and Nerve*, *43*(4), 563–573. doi:10.1002/mus.21981

Kuhn, J. E., Helmer, T. T., Dunn, W. R., & Throckmorton V, T. W. (2011). Development and reliability testing of the frequency, etiology, direction, and severity (FEDS) system for classifying glenohumeral instability. *Journal of Shoulder and Elbow Surgery, 20(4), 548-556.* doi:10.1016/j.jse.2010.10.027

Kumar, A., Tanaka, Y., Grigoriadis, A., Grigoriadis, J., Trulsson, M., & Svensson, P. (2017). Training-induced dynamics of accuracy and precision in human motor control. *Scientific Reports*, *7*(1), 1-10. doi:10.1038/s41598-017-07078-y

Lädermann, A., Denard, P. J., Collin, P., Ibrahim, M., Bothorel, H., & Chih-Hao Chiu, J. (2021). Single Assessment Numeric Evaluation for instability as an alternative to the Rowe score. *Journal of Shoulder and Elbow Surgery*, *30*(5), 1167–1173. doi:10.1016/j.jse.2020.08.013

Lädermann, A., Denard, P. J., Tirefort, J., Kolo, F. C., Chagué, S., Cunningham, G., & Charbonnier, C. (2016). Does surgery for instability of the shoulder truly stabilize the glenohumeral joint?: A prospective comparative cohort study. *Medicine*, *95*(31), e4369. doi:10.1097/md.0000000000004369

Laidlaw, D. H., Kornatz, K. W., Keen, D. A., Suzuki, S., Enoka, R. M., & Enoka Strength, R. M. (1999). Strength training improves the steadiness of slow lengthening contractions performed by old adults. *Journal of Applied Physiology*, *87*(5), 1786–1795. doi:10.1152/jappl.1999.87.5.1786

Lauzière, S., Dubois, B., Brière, A., & Nadeau, S. (2012). Magnitude of force perception errors during static contractions of the knee extensors in healthy young and elderly individuals. *Attention, Perception, and Psychophysics*, *74*(1), 216–224. doi:10.3758/s13414-011-0223-6

Lee, H., Jun Son, S., Kim, H., Han, S., Seeley, M., & Ty Hopkins, J. (2021). Submaximal force steadiness and accuracy in patients with chronic ankle instability. *Journal of Athletic Training*, *56*(5), 454–460. doi:10.4085/15-20

Lee, J. H., Park, J. S., & Jeong, W. K. (2020). Which muscle performance can be improved after arthroscopic Bankart repair? *Journal of Shoulder and Elbow Surgery*, *29*(8), 1681–1688. doi:10.1016/j.jse.2019.12.013

Lephart, S. M., & Jari, R. (2002). The role of proprioception in shoulder instability. *Operative Techniques in Sports Medicine*, *10*(1), 2–4. doi:10.1053/otsm.2002.29169

Lephart, S. M., Warner, J. J. P., Borsa, P. A., & Fu, F. H. (1994). Proprioception of the shoulder joint in healthy, unstable, and surgically repaired shoulders. *Journal of Shoulder and Elbow Surgery*, *3*(6), 371–380. doi:10.1016/S1058-2746(09)80022-0

Levy, D. M., Cole, B. J., & Bach, B. R. (2016). History of surgical intervention of anterior shoulder instability. In *Journal of Shoulder and Elbow Surgery*, 25(6), e139–e150. doi:10.1016/j.jse.2016.01.019

Li, L., Li, Y., Wang, H., Chen, W., & Liu, X. (2020). Effect of force level and gender on pinch force perception in healthy adults. *I-Perception*, *11*(3). doi:10.1177/2041669520927043

Li, L., Li, Y. X., Gong, R., & Fu, H. (2020). Effect of wrist position on grip force sense in healthy adults. *Human Factors and Ergonomics In Manufacturing*, *30*(4), 237–247. doi:10.1002/hfm.20836

Li, T., Wang, D., Peng, C., Yu, C., & Zhang, Y. (2018). Speed-accuracy trade off of fingertip force control with visual/audio/haptic feedback. *International Journal of Human Computer Studies*, *110*, 33–44. doi:10.1016/j.ijhcs.2017.10.004

Limonta, E., Rampichini, S., Cè, E., & Esposito, F. (2015). Effects of visual feedback absence on force control during isometric contraction. *European Journal of Applied Physiology*, *115*(3), 507–519. doi:10.1007/s00421-014-3036-1

Lodha, N., Naik, S. K., Coombes, S. A., & Cauraugh, J. H. (2010). Force control and degree of motor impairments in chronic stroke. *Clinical Neurophysiology*, *121*(11), 1952–1961. doi:10.1016/j.clinph.2010.04.005

Luu, B. L., Day, B. L., Cole, J. D., & Fitzpatrick, R. C. (2011a). The fusimotor and reafferent origin of the sense of force and weight. *Journal of Physiology*, *589*(13), 3135–3147. doi:10.1113/jphysiol.2011.208447

Luu, B. L., Day, B. L., Cole, J. D., & Fitzpatrick, R. C. (2011b). The fusimotor and reafferent origin of the sense of force and weight. *Journal of Physiology*, *589*(13), 3135–3147. doi:10.1113/jphysiol.2011.208447

Ma, X., Lu, L., Zhou, Z., Sun, W., Chen, Y., Dai, G., Wang, C., Ding, L., Fong, D. T. P., & Song, Q. (2022). Correlations of strength, proprioception, and tactile sensation to return-to-sports readiness among patients with anterior cruciate ligament reconstruction. *Frontiers in Physiology*, *13*, 2582. doi:10.3389/fphys.2022.1046141

Macefield, V. G. (2005). Physiological characteristics of low-threshold mechanoreceptors in joints, muscle and skin in human subjects. *Clinical and Experimental Pharmacology and Physiology*, *32*(1–2), 135–144. doi:10.1111/j.1440-1681.2005.04143.x

Macefield, V. G., & Knellwolf, T. P. (2018). Functional properties of human muscle spindles. *Journal of Neurophysiology,*, *120*, 452–467. doi:10.1152/jn.00071.2018.-Muscle

Maenhout, A. G., Palmans, T., De Muynck, M., De Wilde, L. F., & Cools, A. M. (2012). The impact of rotator cuff tendinopathy on proprioception, measuring force sensation. *Journal of Shoulder and Elbow Surgery*, *21*(8), 1080–1086. doi:10.1016/j.jse.2011.07.006

Magni, N. E., McNair, P. J., & Rice, D. A. (2021). Impairments in grip and pinch force accuracy and steadiness in people with osteoarthritis of the hand: A case-control comparison. *Musculoskeletal Science and Practice*, *55*. doi:10.1016/j.msksp.2021.102432

Marmon, A. R., Gould, J. R., & Enoka, R. M. (2011). Practicing a functional task improves steadiness with hand muscles in older adults. *Medicine and Science in Sports and Exercise*, *43*(8), 1531–1537. doi:10.1249/MSS.0b013e3182100439

Marmon, A. R., Pascoe, M. A., Schwartz, R. S., & Enoka, R. M. (2011). Associations among strength, steadiness, and hand function across the adult life span.

Medicine and Science in Sports and Exercise, *43*(4), 560–567. doi:10.1249/MSS.0b013e3181f3f3ab

Mattacola, C. G., Perrin. D. H., Gansneder. B. M., Gieck, J. H., Saliba, E. N., & Mccue, F. C. (2002). Strength, functional outcome, and postural stability after anterior cruciate ligament reconstruction. *Journal of Athletic Training*, *37*(3), 262–268.

Mattern, O., Funk, L., & Walton, M. J. (2018). Anterior shoulder instability in collision and contact athletes. *Journal of Arthroscopy and Joint Surgery*, *5*(2), 99–106. doi:10.1016/j.jajs.2018.05.010

Mccloskey, D. I., Ekeling, P., & Goodwin, M. (1974). Estimation of weights and tensions and apparent involvement of a “sense of effort.” *Experimental Neurology*, *42*, 220–232. doi:10.1016/0014-4886(74)90019-3

McGorry, R. W., Lin, J. H., Dempsey, P. G., & Casey, J. S. (2010). Accuracy of the Borg CR10 scale for estimating grip forces associated with hand tool tasks. *Journal of Occupational and Environmental Hygiene*, *7*(5), 298–306. doi:10.1080/15459621003711360

McIntyre, A. K., Proske, U., & Rawson, J. A. (1984). Cortical projection of afferent information from tendon organs in the cat. *The Journal of Physiology*, *354*(1), 395–406. doi:10.1113/jphysiol.1984.sp015383

McNair, P. J., Stanley, S. N., & Strauss, G. R. (1996). Knee bracing: Effects on proprioception. *Archives of Physical Medicine and Rehabilitation*, *77*(3), 287–289. doi:10.1016/S0003-9993(96)90114-8

Meller, R., Krettek, C., Gösling, T., Wähling, K., Jagodzinski, M., & Zeichen, J. (2007). Recurrent shoulder instability among athletes: Changes in quality of life, sports activity, and muscle function following open repair. *Knee Surgery, Sports Traumatology, Arthroscopy*, *15*(3), 295–304. doi:10.1007/s00167-006-0114-x

Mense, S. (1993). Peripheral mechanism of muscle nociception and local muscle pain. *Journal of Musculoskeletal Pain*, *1*(1), 133–170. doi:10.1300/J094v01n01_10

Mileusnic, M. P., & Loeb, G. E. (2006). Mathematical models of proprioceptors. II. Structure and function of the Golgi tendon organ. *Journal of Neurophysiology*, *96*(4), 1789–1802. doi:10.1152/jn.00869.2005

Mileusnic, M. P., & Loeb, G. E. (2009). Force estimation from ensembles of Golgi tendon organs. *Journal of Neural Engineering*, *6*(3), 036001. doi:10.1088/1741-2560/6/3/036001

Miyamoto, T., Kizuka, T., & Ono, S. (2020). The Influence of Contraction Types on the Relationship Between the Intended Force and the Actual Force. *Journal of Motor Behavior*, *52*(6), 687–693. doi:10.1080/00222895.2019.1680947

Mohammed, K., Cadogan, A., Robinson, D., & Roche, J. (2015). The shoulder in the collision athlete. *Orthopaedics and Trauma*, *29*(3), 195–205. doi:10.1016/j.mporth.2014.12.007

Mohtadi, N. G. H., Chan, D. S., Hollinshead, R. M., Boorman, R. S., Hiemstra, L. A., Lo, I. K. Y., Hannaford, H. N., Fredine, J., Sasyniuk, T. M., & Paolucci, E. O. (2014). A randomized clinical trial comparing open and arthroscopic stabilization for recurrent traumatic anterior shoulder instability: Two-year follow-up with disease-specific quality-of-life outcomes. *Journal of Bone and Joint Surgery*, *96*(5), 353–360. doi:10.2106/JBJS.L.01656

Monjo, F., & Forestier, N. (2018). Muscle spindle thixotropy affects force perception through afferent-induced facilitation of the motor pathways as revealed by the Kohnstamm effect. *Experimental Brain Research*, *236*(4), 1193–1204. doi:10.1007/s00221-018-5207-5

Monjo, F., Shemmell, J., & Forestier, N. (2018). The sensory origin of the sense of effort is context-dependent. *Experimental Brain Research*, 26(7), 1997-2008. doi:10.1007/s00221-018-5280-9

Moore, J. C. (1984). The Golgi Tendon Organ: A Review and Update. *The American Journal of Occupational Therapy*, *38*(4), 227–236. doi:10.5014/ajot.38.4.227

Moritz, C. T., Barry, B. K., Pascoe, M. A., & Enoka, R. M. (2005). Discharge rate variability influences the variation in force fluctuations across the working range of a hand muscle. *Journal of Neurophysiologyhttps://Doi.Org/10.1152/Jn.01122.2004*, *93*(5), 2449–2459. doi:10.1152/jn.01122.2004

Myers, J. B., Ju, Y. Y., Hwang, J. H., McMahon, P. J., Rodosky, M. W., & Lephart, S. M. (2004). Reflexive muscle activation alterations in shoulders with anterior glenohumeral instability. *American Journal of Sports Medicine*, *32*(4), 1013–1021. doi:10.1177/0363546503262190

Myers, J. B., & Lephart, S. M. (2000). The Role of the Sensorimotor System in the Athletic Shoulder. *Journal of Athletic Training*, *35*(3), 351–363.

Myers, J. B., Wassinger, C. A., & Lephart, S. M. (2006). Sensorimotor contribution to shoulder stability: Effect of injury and rehabilitation. *Manual Therapy*, *11*(3), 197–201. doi:10.1016/j.math.2006.04.002

Noble, J. W., Eng, J. J., & Boyd, L. A. (2013). Effect of visual feedback on brain activation during motor tasks: An fMRI study. *Motor Control*, *17*(3), 298–312. doi:10.1123/mcj.17.3.298

Nomura, Y., Kuramochi, R., & Fukubayashi, T. (2015). Evaluation of hamstring muscle strength and morphology after anterior cruciate ligament reconstruction. *Scandinavian Journal of Medicine and Science in Sports*, *25*(3), 301–307. doi:10.1111/sms.12205

Nyland, J., Caborn, D., & Johnson, D. (1998). The human glenohumeral joint A proprioceptive and stability alliance. *Knee Surgery*, *6*, 50–61. doi:10.1007/s001670050072

Ogawa, K., Yoshida, A., & Ikegami, H. (2006). Osteoarthritis in shoulders with traumatic anterior instability: Preoperative survey using radiography and computed tomography. *Journal of Shoulder and Elbow Surgery*, *15*(1), 23–29. doi:10.1016/j.jse.2005.05.011

Olds, M., Coulter, C., Marrant, D., & Uhl, T. (2019). Reliability of a shoulder arm return to sport test battery. *Physical Therapy in Sport*, *39*, 16–22. doi:10.1016/j.ptsp.2019.06.001

Olds, M., Ellis, R., Donaldson, K., Parmar, P., & Kersten, P. (2015). Risk factors which predispose first-time traumatic anterior shoulder dislocations to recurrent instability in adults: A systematic review and meta-analysis. *British Journal of Sports Medicine*, *49*(14), 913–922. doi:10.1136/bjsports-2014-094342

Olds, M., Gadkari, P., & Adams, T. (2020). Normative Rugby Data of the SARTS Tests: Comparison of Elite and School Players. *International Journal of Sports Medicine*, *41*(11), 771–775. doi:10.1055/a-1171-1664

Olds, M., & Webster, K. E. (2021). Factor structure of the shoulder instability return to sport after injury scale: performance confidence, reinjury fear and risk, emotions, rehabilitation and surgery. *American Journal of Sports Medicine*, *49*(10), 2737–2742. doi:10.1177/03635465211024924

Onneweer, B., Mugge, W., & Schouten, A. C. (2016a). Force Reproduction Error Depends on Force Level, whereas the Position Reproduction Error Does Not. *IEEE Transactions on Haptics*, *9*(1), 54–61. doi:10.1109/TOH.2015.2508799

Onneweer, B., Mugge, W., & Schouten, A. C. (2016b). Force reproduction error depends on force Level, whereas the position reproduction error does not. *IEEE Transactions on Haptics*, *9*(1), 54–61. doi:10.1109/TOH.2015.2508799

Ottenbacher, K. J. (1991). Statistical conclusion validity. Multiple inferences in rehabilitation research. *American Journal of Physical Medicine & Rehabilitation*, *70*(6), 317–322.

Owens, B. D., Nelson, B. J., Duffey, M. L., Mountcastle, S. B., Taylor, D. C., Cameron, K. L., Campbell, S., & DeBerardino, T. M. (2010). Pathoanatomy of first-time, traumatic, anterior glenohumeral subluxation events. *Journal of Bone and Joint Surgery*, *92*(7), 1605–1611. doi:10.2106/JBJS.I.00851

Pagnani, M. J., Deng, X.-H., Warren, R. F., Torzilli, P. A., O, S. J., & York, N. (1996). Role of the long head of the biceps brachii in glenohumeral stability: A biomechanical study in cadavera. *Surgery*, *5*(4), 255–262. doi:10.1016/S1058-2746(96)80051-6

Park, I., Lee, J. H., Hyun, H. S., Lee, T. K., & Shin, S. J. (2018). Minimal clinically important differences in Rowe and Western Ontario Shoulder Instability Index scores after arthroscopic repair of anterior shoulder instability. *Journal of Shoulder and Elbow Surgery*, *27*(4), 579–584. doi:10.1016/j.jse.2017.10.032

Park, W. H., Leonard, C. T., & Li, S. (2008). Finger force perception during ipsilateral and contralateral force matching tasks. *Experimental Brain Research*, *189*(3), 301–310. doi:10.1007/s00221-008-1424-7

Peng, C., Wang, D., Zhang, Y., & Li, T. (2017). Quantifying differences between five fingers in speed-accuracy tradeoff for force control tasks. *2017 IEEE World Haptics Conference, WHC 2017*, 275–280. doi:10.1109/WHC.2017.7989914

Perraton, L., Clark, R., Crossley, K., Pua, Y. H., Whitehead, T., Morris, H., Telianidis, S., & Bryant, A. (2017). Impaired voluntary quadriceps force control following anterior cruciate ligament reconstruction: relationship with knee function. *Knee Surgery, Sports Traumatology, Arthroscopy*, *25*(5), 1424–1431. doi:10.1007/s00167-015-3937-5

Perraton, L., Clark, R., Crossley, K., Pua, Y.-H., Whitehead, T., Morris, H., Telianidis, S., & Bryant, A. (2017b). Impaired voluntary quadriceps force control following anterior cruciate ligament reconstruction: relationship with knee function. *Knee Surgery, Sports Traumatology, Arthroscopy*, *25*(5), 1424–1431. doi:10.1007/s00167-015-3937-5

Perraton, L., Telianidis, S., Clark, R., Pua, Y., Crossley, K., & Bryant, A. (2013). Quadriceps muscle force control is related to knee function 12 months after anterior cruciate ligament reconstruction. *Journal of Science and Medicine in Sport*, *16*, e91–e92. doi:10.1016/j.jsams.2013.10.219

Phillips, D., & Karduna, A. (2018). No relationship between joint position sense and force sense at the shoulder. *Journal of Motor Behavior*, *50*(2), 228–234. doi:10.1080/00222895.2017.1327415

Pietrosimone, B., Lepley, A. S., Kuenze, C., Harkey, M. S., Hart, J. M., & Blackburn, J. T. (2022). Arthrogenic muscle inhibition following anterior cruciate ligament Injury. *Journal of Sport Rehabilitation*, *31(6),* 694–706. doi:10.1123/jsr.2021-0128

Pötzl, W., Thorwesten, L., Götze, C., Garmann, S., & Steinbeck, J. (2004). Proprioception of the shoulder joint after surgical repair for instability: A long-term follow-up study. *American Journal of Sports Medicine*, 32(2), 425–430. doi:10.1177/0363546503261719

Poulet, J. F. A., & Hedwig, B. (2007). New insights into corollary discharges mediated by identified neural pathways. *Trends in Neurosciences*, *30(1),* 14–21. doi:10.1016/j.tins.2006.11.005

Proske, U. (1997). The mammalian muscle spindle. *Physiology,* 12(1), 37-42. doi:10.1152/physiologyonline.1997.12.1.37

Proske, U. (2005). What is the role of muscle receptors in proprioception? *Muscle and Nerve*, *31(6),* 780–787. doi:10.1002/mus.20330

Proske, U., & Allen, T. (2019a). The neural basis of the senses of effort, force and heaviness. *Experimental Brain Research*, 273(3), 589-599. doi:10.1007/s00221-018-5460-7

Proske, U., & Allen, T. (2019b). The neural basis of the senses of effort, force and heaviness. In *Experimental Brain Research*, 237(3), 589–599. doi:10.1007/s00221-018-5460-7

Proske, U., & Gandevia, S. C. (2009). The kinaesthetic senses. In *Journal of Physiology,* 587(17), 4139–4146. doi:10.1113/jphysiol.2009.175372

Proske, U., & Gandevia, S. C. (2012). The proprioceptive senses: Their roles in signaling body shape, body position and movement, and muscle force. *Physiological Reviews*, *92*(4), 1651–1697. doi:10.1152/physrev.00048.2011

Proske, U., Gregory, J. E., Morgan, D. L., Percival, P., Weerakkody, N. S., & Canny, B. J. (2004). Force matching errors following eccentric exercise. *Human Movement Science*, 23(3-4), 365-378. doi:10.1016/j.humov.2004.08.012

Provencher, M. T., Midtgaard, K. S., Owens, B. D., & Tokish, J. M. (2021). Diagnosis and management of traumatic anterior shoulder instability. *Journal of the American Academy of Orthopaedic Surgeons*, *29*(2), e51–e61. doi:10.5435/JAAOS-D-20-00202

Rice, D. A., & McNair, P. J. (2010). Quadriceps arthrogenic muscle inhibition: Neural mechanisms and treatment perspectives. *Seminars in Arthritis and Rheumatism*, *40*(3), 250–266. doi:10.1016/j.semarthrit.2009.10.001

Rice, D. A., McNair, P. J., Lewis, G. N., & Mannion, J. (2015). Experimental knee pain impairs submaximal force steadiness in isometric, eccentric, and concentric muscle actions. *Arthritis Research and Therapy*, *17*(1), 1–6. doi:10.1186/s13075-015-0768-1

Rice, D., Lewis, G., & McNair, P. (2021). Impaired Regulation of Submaximal Force after ACL Reconstruction: Role of Muscle Spindles. *International Journal of Sports Medicine*, *42*(6), 550–558. doi:10.1055/a-1292-4461

Riehle, A., MacKay, W. A., & Requin, J. (1994). Are extent and force independent movement parameters? Preparation- and movement-related neuronal activity in the monkey cortex. *Experimental Brain Research*, *99*(1), 56–74. doi:10.1007/BF00241412

Rokito, A. S., Birdzell, M. G., Cuomo, F., Di Paola, M. J., & Zuckerman, J. D. (2010). Recovery of shoulder strength and proprioception after open surgery for recurrent anterior instability: A comparison of two surgical techniques. *Journal of Shoulder and Elbow Surgery*, *19*(4), 564–569. doi:10.1016/j.jse.2009.09.010

Roland, P. E., & Ladegaard-Pedersen, H. (1977). A quantitative analysis of sensations of tension and of kinaesthesia in man: Evidence for a peripherally originating muscular sense and for a sense of effort. *Brain*, *100*(4), 671–692. doi:10.1093/brain/100.4.671

Rossi, L. A., Pasqualini, I., Brandariz, R., Fuentes, N., Fieiras, C., Tanoira, I., & Ranalletta, M. (2022). Relationship of the SIRSI Score to Return to Sports After Surgical Stabilization of Glenohumeral Instability. *American Journal of Sports Medicine*, *50*(12), 3318–3325. doi:10.1177/03635465221118369

Rowe, C. R., Patel, D., & Southmayd, W. W. (1978). The Bankart procedure: A long-term end result study. *Journal of Bone and Joint Surgery, 60(1),* 1-16.

Saccol, M. F., Zanca, G. G., Ejnisman, B., de Mello, M. T., & Mattiello, S. M. (2014). Shoulder rotator strength and torque steadiness in athletes with anterior shoulder instability or SLAP lesion. *Journal of Science and Medicine in Sport*, *17*(5), 463–468. doi:10.1016/j.jsams.2013.10.246

Salonikidis, K., Amiridis, I. G., Oxyzoglou, N., De Villareal, E. S. S., Zafeiridis, A., & Kellis, E. (2009). Force variability during isometric wrist flexion in highly skilled and sedentary individuals. *European Journal of Applied Physiology*, *107*(6), 715–722. doi:10.1007/s00421-009-1184-5

Sarlegna, F. R., Baud-Bovy, G., & Danion, F. (2010). Delayed visual feedback affects both manual tracking and grip force control when transporting a handheld object. *Journal of Neurophysiology*, *104*(2), 641–653. doi:10.1152/jn.00174.2010

Schmitt, L. C., Paterno, M. V., Ford, K. R., Myer, G. D., & Hewett, T. E. (2015). Strength asymmetry and landing mechanics at return to sport after anterior cruciate ligament reconstruction. *Medicine and Science in Sports and Exercise*, *47*(7), 1426–1434. doi:10.1249/MSS.0000000000000560

Sergio, L. E., Hamel-Pâquet, C., & Kalaska, J. F. (2005). Motor cortex neural correlates of output kinematics and kinetics during isometric-force and arm-reaching tasks. *Journal of Neurophysiology*, *94*(4), 2353–2378. doi:10.1152/jn.00989.2004

Shafer, R. L., Solomon, E. M., Newell, K. M., Lewis, M. H., & Bodfish, J. W. (2019). Visual feedback during motor performance is associated with increased complexity and adaptability of motor and neural output. *Behavioural Brain Research*, *376*, 112214. doi:10.1016/j.bbr.2019.112214

Sherwood, D. E., & Schmidt, R. A. (1980). The relationship between force and force variability in minimal and near-maximal static and dynamic contractions. *Journal of Motor Behavior*, *12*(1), 75–89. doi:10.1080/00222895.1980.10735208

Slifkin, A. B., & Newell, K. M. (1999). Noise, information transmission, and force variability. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(3), 837–851. doi:10.1037/0096-1523.25.3.837

Sousa, A. S. P., Leite, J., Costa, B., & Santos, R. (2017). Bilateral proprioceptive evaluation in individuals with unilateral chronic ankle instability. *Journal of Athletic Training*, *52*(4), 360–367. doi:10.4085/1062-6050-52.2.08

Sperry, R. W. (1950). Neural basis of the spontaneous optokinetic response produced by visual inversion. *Journal of Comparative and Physiological Psychology*, *43*(6), 482. doi:10.1037/h0055479

Spraker, M. B., Yu, H., Corcos, D. M., & Vaillancourt, D. E. (2007). Role of individual basal ganglia nuclei in force amplitude generation. *Journal of Neurophysiology*, *98*(2), 821–834. doi:10.1152/jn.00239.2007

Stillman, B. C. (2002). Making sense of proprioception. *Physiotherapy*, *88*(11), 667–676. doi:10.1016/S0031-9406(05)60109-5

Taira, M., Boline, J., Smyrnis, N., Georgopoulos, A. P., & Ashe, J. (1996). On the relations between single cell activity in the motor cortex and the direction and magnitude of three-dimensional static isometric force. *Experimental Brain Research*, *109*(3), 367–376. doi:10.1007/BF00229620

Taylor, A. M., Christou, E. A., & Enoka, R. M. (2003). Multiple features of motor-unit activity influence force fluctuations during isometric contractions. *Journal of Neurophysiology*, *90*(2), 1350–1361. doi:10.1152/jn.00056.2003

Taylor, J. L., Butler, J. E., & Gandevia, S. C. (2000). Changes in muscle afferents, motoneurons and motor drive during muscle fatigue. *European Journal of Applied Physiology*, *83*, 106–115. doi:10.1007/s004210000269

Telianidis, S., Perraton, L., Clark, R. A., Pua, Y. H., Fortin, K., & Bryant, A. L. (2014). Diminished sub-maximal quadriceps force control in anterior cruciate ligament reconstructed patients is related to quadriceps and hamstring muscle dyskinesia. *Journal of Electromyography and Kinesiology*, *24*(4), 513–519. doi:10.1016/j.jelekin.2014.04.014

Thomeé, R., Neeter, C., Gustavsson, A., Thomeé, P., Augustsson, J., Eriksson, B., & Karlsson, J. (2012). Variability in leg muscle power and hop performance after anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy*, *20*(6), 1143–1151. doi:10.1007/s00167-012-1912-y

Tjong, V. K., Devitt, B. M., Murnaghan, M. L., Ogilvie-Harris, D. J., & Theodoropoulos, J. S. (2015). A qualitative investigation of return to sport after arthroscopic bankart repair: Beyond stability. *American Journal of Sports Medicine*, *43*(8), 2005–2011. doi:10.1177/0363546515590222

Tracy, B. L. (2007). Visuomotor contribution to force variability in the plantarflexor and dorsiflexor muscles. *Human Movement Science*, *26*(6), 796–807. doi:10.1016/j.humov.2007.07.001

Tracy, B. L., Dinenno, D. V., Jorgensen, B., & Welsh, S. J. (2007). Aging, visuomotor correction, and force fluctuations in large muscles. *Medicine and Science in Sports and Exercise*, *39*(3), 469–479. doi:10.1249/mss.0b013e31802d3ad3

Troiano, A., Naddeo, F., Sosso, E., Camarota, G., Merletti, R., & Mesin, L. (2008). Assessment of force and fatigue in isometric contractions of the upper trapezius muscle by surface EMG signal and perceived exertion scale. *Gait and Posture*, *28*(2), 179–186. doi:10.1016/j.gaitpost.2008.04.002

Trousset, K., Phillips, D., & Karduna, A. (2018). An investigation into force sense at the shoulder. *Motor Control*, *22*(4), 462–471. doi:10.1123/mc.2017-0067

Tsai, L. I., Gibo, K., & Tornqvist, H. (1991). Shoulder function in patients with unoperated anterior shoulder instability. *The American Journal of Sports Medicine*, *19*(5), 469–473. doi:10.1177/036354659101900508

Tuoheti, Y., Itoi, E., Minagawa, H., Wakabayashi, I., Kobayashi, M., Okada, K., & Shimada, Y. (2005). Quantitative assessment of thinning of the subscapularis tendon in recurrent anterior dislocation of the shoulder by use of magnetic resonance imaging. *Journal of Shoulder and Elbow Surgery*, *14*(1), 11–15. doi:10.1016/j.jse.2004.04.009

Turkel, S. J., Panio, M. W., Marshall, J. L., & Girgis, F. G. (1981). Stabilizing mechanisms preventing anterior dislocation of the glenohumeral joint. *Journal of Bone and Joint Surgery*, *63*(8), 1208–1217. doi:10.2106/00004623-198163080-00002

Vaillancourt, D. E., & Russell, D. M. (2002). Temporal capacity of short-term visuomotor memory in continuous force production. *Experimental Brain Research*, *145*(3), 275–285. doi:10.1007/s00221-002-1081-1

Vaillancourt, D. E., Thulborn, K. R., & Corcos, D. M. (2003). Neural basis for the processes that underlie visually guided and internally guided force control in humans. *Journal of Neurophysiology*, *90*(5), 3330–3340. doi:10.1152/jn.00394.2003

Vallbo, B. (1971). Muscle spindle response at the onset of isometric voluntary contractions in man. Time difference between fusimotor and skeletomotor effects. *The Journal of Physiology*, *218*(2), 405–431. doi:10.1113/jphysiol.1971.sp009625

Van Der Linde, J. A., Van Kampen, D. A., Van Beers, L. W. A. H., Van Deurzen, D. F. P., Saris, D. B. F., & Terwee, C. B. (2017). The responsiveness and minimal important change of the western Ontario shoulder instability index and oxford shoulder instability score. *Journal of Orthopaedic and Sports Physical Therapy*, *47*(6), 402–410. doi:10.2519/jospt.2017.6548

Vascellari, A., Ramponi, C., Venturin, D., Ben, G., Blonna, D., & Coletti, N. (2018). The Degree of Shoulder Involvement in Sports (DOSIS) scale is a valid and responsive instrumentation for shoulder assessment in patients after surgery for anterior instability. *Knee Surgery, Sports Traumatology, Arthroscopy*, *26*(1), 195–202. doi:10.1007/s00167-017-4642-3

Vascellari, A., Ramponi, C., Venturin, D., Ben, G., & Coletti, N. (2019). The relationship between kinesiophobia and return to sport after shoulder surgery for recurrent anterior instability. *Joints*, *7*(4), 148–154. doi:10.1055/s-0041-1730975

Vila-Chã, C., & Falla, D. (2016). Strength training, but not endurance training, reduces motor unit discharge rate variability. *Journal of Electromyography and Kinesiology*, *26*, 88–93. doi:10.1016/j.jelekin.2015.10.016

Walsh, L. D., Taylor, J. L., & Gandevia, S. C. (2011). Overestimation of force during matching of externally generated forces. *Journal of Physiology*, *589*(3), 547–557. doi:10.1113/jphysiol.2010.198689

Wang, Y., Feng, S., Yang, R., Hou, W., Wu, X., & Chen, L. (2022). The learning-relative hemodynamic modulation of cortical plasticity induced by a force-control motor training. *Frontiers in Neuroscience*, *8*(16), 1–14. doi:10.3389/fnins.2022.922725

Ward, S. H., Perraton, L., Bennell, K., Pietrosimone, B., & Bryant, A. L. (2019). Deficits in quadriceps force control after anterior cruciate ligament injury: Potential central mechanisms. *Journal of Athletic Training*, *54*(5), 505–512. doi:10.4085/1062-6050-414-17

Warren, R. M. (1981). Measurement of sensory intensity. *Behavioral and Brain Sciences*, *4*(2), 175–189. doi:10.1017/S0140525X00008256

Weerakkody, N., Percival, P., Morgan, D. L., Gregory, J. E., & Proske, U. (2003a). Matching different levels of isometric torque in elbow flexor muscles after eccentric exercise. *Experimental Brain Research*, *149*(2), 141–150. doi:10.1007/s00221-002-1341-0

Weerakkody, N., Percival, P., Morgan, D. L., Gregory, J. E., & Proske, U. (2003b). Matching different levels of isometric torque in elbow flexor muscles after eccentric exercise. *Experimental Brain Research*, *149*(2), 141–150. doi:10.1007/s00221-002-1341-0

Weerakkody, N., Percival, P., Morgan, D. L., Gregory, J. E., & Proske, U. (2003c). Matching different levels of isometric torque in elbow flexor muscles after eccentric exercise. *Experimental Brain Research*, *149*(2), 141–150. doi:10.1007/s00221-002-1341-0

Werner, C. M. L., Favre, P., & Gerber, C. (2007). The role of the subscapularis in preventing anterior glenohumeral subluxation in the abducted, externally rotated position of the arm. *Clinical Biomechanics*, *22*(5), 495–501. doi:10.1016/j.clinbiomech.2006.12.007

Wilk, K. E., Bagwell, M. S., Davies, G. J., & Arrigo, C. A. (2020). Return to sport participation criteria following shoulder injury: A clinical commentary. *International Journal of Sports Physical Therapy*, *15*(4), 624–642. doi:10.26603/ijspt20200624

Williams, W. N., Coffey, J., Turner, G. E., Crary, M. E., Capen, R., & Wharton, P. W. (1992). Level of accuracy and degree of precision in attempting to maintain steady levels of biting force. *Journal of Oral Rehabilitation*, *19*(6), 655–662. doi:10.1111/j.1365-2842.1992.tb01495.x

Wilson, K. W., Popchak, A., Li, R. T., Kane, G., & Lin, A. (2020). Return to sport testing at 6 months after arthroscopic shoulder stabilization reveals residual strength and functional deficits. *Journal of Shoulder and Elbow Surgery*, *29*(7), S107–S114. doi:10.1016/j.jse.2020.04.035

Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An Internal Model for Sensorimotor Integration. *Science*, *269*(5232), 1880–1882. doi:10.1126/science.7569931

Wright, A., Monga, P., Richards, J., & Selfe, J. (2015). Three dimensional analysis of shoulder movement patterns in shoulders with anterior instability: A comparison of kinematics with normal shoulders and the influence of stabilisation surgery. *Gait & Posture*, *1*(42), S31–S32. doi:10.1016/j.gaitpost.2015.06.063

Wright, C. J., & Arnold, B. L. (2012). Fatigue’s Effect on Eversion Force Sense in Individuals With and Without Functional Ankle Instability. In *Journal of Sport Rehabilitation*, 21(2), 127-136. doi:10.1123/

Yen, S. C., Chui, K. K., Wang, Y. C., Corkery, M. B., Nabian, M., & Farjadian, A. B. (2019). An examination of muscle force control in individuals with a functionally unstable ankle. *Human Movement Science*, *64*, 221–229. doi:10.1016/j.humov.2019.02.005

Yildiz, T. I., Turhan, E., Ocguder, D. A., Yaman, F., Huri, G., & Duzgun, I. (2022). Functional performance tests reveal promising results at 6 months after shoulder stabilization surgery. *Sports Health,* 1-8. doi:10.1177/19417381221141075

Yoon, T., Vanden Noven, M. L., Nielson, K. A., & Hunter, S. K. (2014). Brain areas associated with force steadiness and intensity during isometric ankle dorsiflexion in men and women. *Experimental Brain Research*, *232*(10), 3133–3145. doi:10.1007/s00221-014-3976-z

Zanca, G. G., Camargo, P. R., Oliveira, A. B., Serrão, P. R. M. S., & Mattiello-Rosa, S. M. (2010). Isometric medial and lateral rotations torque steadiness in female workers with shoulder impingement. *Isokinetics and Exercise Science*, *18*(3), 115–118. doi:10.3233/IES-2010-0368

Zanca, G. G., Saccol, M. F., Oliveira, A. B., & Mattiello, S. M. (2013). Shoulder internal and external rotations torque steadiness in overhead athletes with and without impingement symptoms. *Journal of Science and Medicine in Sport*, *16*(5), 433–437. doi:10.1016/j.jsams.2012.09.004

Zuckerman, J. D., Gallagher, M. A., Cuomo, F., & Rokito, A. (2003). The effect of instability and subsequent anterior shoulder repair on proprioceptive ability. *Journal of Shoulder and Elbow Surgery*, *12*(2), 105–109. doi:10.1067/mse.2003.4

Zult, T., Gokeler, A., van Raay, J. J. A. M., Brouwer, R. W., Zijdewind, I., & Hortobágyi, T. (2017). An anterior cruciate ligament injury does not affect the neuromuscular function of the non-injured leg except for dynamic balance and voluntary quadriceps activation. *Knee Surgery, Sports Traumatology, Arthroscopy*, *25*(1), 172–183. doi:10.1007/s00167-016-4335-3

Appendices

Appendix A: Ethics Approval

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

5 October 2020

Peter McNair
Faculty of Health and Environmental Sciences

Dear Peter

Re Ethics Application: **20/236 Force appreciation, perceived function and physical performance in surgically stabilised shoulders for recurrent anterior instability.**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 5 October 2023.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.
7. It is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard and that all the dates on the documents are updated.

AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

Please quote the application number and title on all future correspondence related to this project.

For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through http://www.aut.ac.nz/research/researchethics

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: pradnyagadkari@yahoo.com

Appendix B: Study Advertisements

A Study to Examine the Strength, Physical Performance and Force appreciation of the shoulder muscles after arthroscopic stabilisation surgery for recurrent anterior instability.

Volunteers Required!

- Participants with anterior stabilisation surgery for recurrent anterior shoulder instability and are approximately six months post-surgery are invited to apply.
- Participants must have clearance from their surgeon or physiotherapist to participate in exercise and rehabilitation in order to be eligible for participation.
- Participants must be able to understand written and spoken English and must be aged between 17-45 years.
- Participants must not have any known neurological or cardiovascular conditions, must not have any previous shoulder surgery, must not have ongoing neck pain, shoulder pain, or any other known bone, joint or muscle conditions.

For further information please contact:

Contact Pradnya
M: 021 919 620
E: pradnyagadkari@yahoo.com

Appendix C: Study Consent Form

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Consent Form

Project title: Force appreciation, perceived function, and physical performance in surgically stabilised shoulders for recurrent anterior instability.

Project Supervisor: Professor Peter McNair

Researcher: Pradnya Gadkari

○ I have read and understood the information provided about this research project in the Information Sheet dated 6th July 2020.

○ I have had an opportunity to ask questions and to have them answered.

○ I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.

○ I understand that if I withdraw from the study then I will be offered the choice between having any data that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.

○ I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any neurological illness, any infection, any history of neck or shoulder pain in the past 6 months, any previous history of shoulder injury(excluding recurrent dislocation/subluxation) or surgery, co-existing rotator cuff tears, Hill Sach's lesion in my surgically repaired shoulder, or previous notable shoulder injury in my unaffected shoulder that impairs my physical performance.

○ I have been given clearance by my orthopaedic surgeon and/or physiotherapist to participate in rehabilitation and exercise.

○ I agree to take part in this research.

○ I wish to receive a summary of the research findings (please tick one): Yes○ No○

Participant's signature: ....

Participant's name: ....

Participant's Contact Details (if appropriate):

………………………………………………………………………………………..

………………………………………………………………………………………..

………………………………………………………………………………………..

………………………………………………………………………………………..

Date:

Approved by the Auckland University of Technology Ethics Committee on 5th October 2020 AUTEC Reference number 20/236

Note: The Participant should retain a copy of this form.

Appendix D: Participant Information Sheet

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Participant Information Sheet

Date Information Sheet Produced:

5th July 2020

Project Title

Force appreciation, perceived function and physical performance in surgically stabilised shoulders for recurrent anterior instability.

An Invitation

My name is Pradnya Gadkari. I am a physiotherapist and Masters Student at the Health and Rehabilitation Institute, Faculty of Health and Environmental Sciences, School of Clinical Sciences at AUT. I would like to invite you to take part in our project called 'Force appreciation, perceived function and physical performance in surgically stabilised shoulders for recurrent anterior instability'. This research project will help me gain my qualification in Masters in Health Science. Participation in this study is voluntary and will not affect your ability to access healthcare and physiotherapy services in the future. You may withdraw from this study at any time point without any consequence.

What is the purpose of this research?

The purpose of this research is to examine the muscle force appreciation of the shoulder internal and external rotators after arthroscopic stabilisation surgery and compare this to your unaffected shoulder at approximately 6 months after surgery. Muscle force appreciation contributes to neuromuscular stability at the shoulder, and good stability is important for preventing recurrence of shoulder instability. Therefore, it is important to understand muscle force appreciation of shoulder internal and external rotators muscles at 6 months post-surgery, a common point for people to be given clearance to return to sports. In addition, physical performance will be examined with clinical tests and perceived function will be assessed by use of questionnaires. This research will be a part of Masters thesis and will be written up for publication in an international journal. The results of this research may also be presented at national and international physiotherapy and sports medicine conferences.

How was I identified and why am I being invited to participate in this research?

You have responded to an advertisement or been verbally informed of this study which directed you to contacting me. You would have had an arthroscopic stabilisation surgery for your recurrent anterior instability. You will have clearance from your orthopaedic surgeon and/or physiotherapist to participate in rehabilitation and exercise. You may be excluded from this study if you have any known neurological, cardiovascular or bone and joint diseases, if you had a previous shoulder injury or surgery, ongoing neck or shoulder pain or do not understand spoken and/or written English.

How do I agree to participate in this research?

Your participation in this research is voluntary (it is your choice) and whether or not you choose to participate will neither advantage nor disadvantage you. You are able to withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal of your data may not be possible.

What will happen in this research?

If you choose to participate in this study, you will be required to attend one session at the Biomechanics Lab, Health and Rehabilitation Institute, AUT Northshore Campus, Akoranga Drive, Northcote, Auckland. This session will be for 60-90 minutes. At this session you will be asked to complete a consent form for this study before testing starts, and some written questionnaires related to your shoulder and health.

Once you have completed the questionnaires the strength of your shoulder internal and external rotator muscles will be tested using Biodex isokinetic dynamometer. You will be seated with your shoulder at 90 degrees abduction and maximum external rotation range achievable and elbow bent at 90 degrees. After an adequate warm up you will be asked to exert as much as effort as you can while turning your arm in and out against the forearm support that holds the arm in a static position. Three trials will be given for each movement and both shoulders will be tested. The results will be recorded on the computer. After the strength testing, muscle force appreciation will be tested in two different methods. In the first testing a target force line will be presented going from left to right at the mid-point on the computer screen. You will be asked to produce muscle force as quickly as possible to match that line for a 15 second time period. In the second test, the target force will be presented as a sinusoidal curve with target force varying between 10% to 65% of your maximum strength. You will be asked to match this curve as closely as possible for 15 sec (Fig 1.). This testing will usually take about 15 minutes at each shoulder. You will be given careful instructions throughout the tests, and there will be an opportunity to practice the movements and warm up prior to the formal test. After completion of force appreciation testing, your shoulder physical performance will be tested to assess your readiness to return to sport with use three tests from of SARTS (Shoulder Arm Return to Sports) battery of tests. You will be asked to perform a side hold rotation, single arm line hop, and a BABER (ball abduction external rotation) test holding a 3kg medicine ball (Fig 2.) . Each test will be for 1min on both arms. This testing will take about 10-15 minutes.

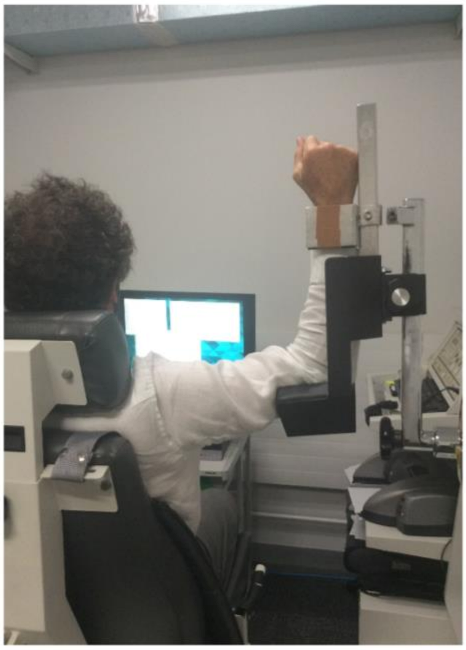


Figure 1. Biodex

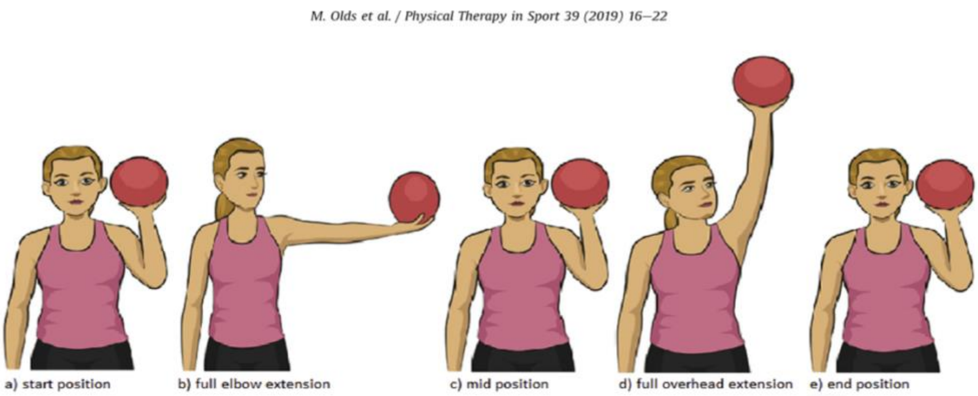


Figure 2.

What are the discomforts and risks?

There are no significant risks associated with these tests. The strength, force appreciation and shoulder physical performance tests are recommended for individuals returning to sports after shoulder stabilisation surgery to assess shoulder function, neuromuscular control and recovery. However, there is a risk that you might experience some mild discomfort in the shoulder or muscles around the shoulder. This discomfort should not be more than that experienced when muscles have worked hard over a 10-minute period.

How will these discomforts and risks be alleviated?

If you encounter greater discomfort than described above during testing, you may stop. A physiotherapist who has the appropriate knowledge and skill to manage pain, swelling and irritation of the shoulder will be carrying out all tests and thus will be able to provide appropriate advice to you on how manage any discomfort. In in the unusual circumstance if you require treatment for ongoing shoulder discomfort, then that should be sought from your GP or from the physiotherapist who had been/or is treating you. If you do not have a physiotherapist then you will be able to select one through the Physiotherapy New Zealand website, the link for which is provided at the end of this information sheet.

What are the benefits?

Participation in this study will provide you with information regarding your shoulder muscle strength, and shoulder muscle performance and readiness to return to sport. It will identify any deficits in your shoulder strength, neuromuscular control and performance and you could use this information to improve your shoulder function further to facilitate returning to sports. This information may also help to guide rehabilitation protocols in the future, reduce risk of re-injury, and provide more information about a safe return to sport post arthroscopic shoulder stabilisation surgery. This study is part of a Masters thesis, and such will help me to gain a qualification in Masters in Health Science.

What compensation is available for injury or negligence?

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for your injury may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my privacy be protected?

When you enter the study, you will be given an identification code and your name will not be used on data/records related to the data collected. The consent form will contain both your name and identification code and this will be stored under lock and key at the School of Clinical Sciences, AUT Northshore Campus. Only the primary researcher and her supervisor will have access to this form. Any data collected in writing will contain your unique identification code only. You will not be identifiable in the final report.

What are the costs of participating in this research?

There are no direct costs associated with participation in this study, only your personal time. The testing session is expected to last no more than 90 minutes. You will receive a small token of appreciation for your time and participation.

What opportunity do I have to consider this invitation?

You have at least 2 weeks to consider this invitation. We will contact you 7 days after you receive this information sheet. If you require more time to consider this invitation, please let us know.

Will I receive feedback on the results of this research?

A one-page summary of the study results will be sent to you via post or email upon completion of the study and data analysis unless you indicate otherwise on your consent form.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Professor Peter McNair, *peter.mcnair@aut.ac.nz* , +64 9 921 9999 ext 7143

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, *ethics@aut.ac.nz* , (+649) 921 9999 ext 6038.

Whom do I contact for further information about this research?

Please keep this Information Sheet and a copy of the Consent Form for your future reference. You are also able to contact the research team as follows:

Researcher Contact Details:

Pradnya Gadkari AUT University, North Shore Campus.

Ph: 021919620

Email: pradnyagadkari@yahoo.com

Project Supervisor Contact Details:

Dr. Peter McNair AUT University, North Shore Campus.

Ph: +64 9 921 9999 Ext 7143

Email: petermcnair@aut.ac.nz

Physiotherapy New Zealand :

https://physio.org.nz/#find-a-physio

Approved by the Auckland University of Technology Ethics Committee on *5th October 2020*, AUTEC Reference number *20/236*

Appendix E: Questionnaire Relating to Demographic and Other Details

Demographic and Health Questionnaire

Patient initial:

Date of Birth:

Gender:

- ☐ Male
- ☐ Female

Ethnicity:

- ☐ New Zealand Maori
- ☐ Pasifika
- ☐ NZ European/Pakeha
- ☐ Asian
- ☐ Middle Eastern
- ☐ African
- ☐ Latin American/Hispanic
- ☐ Other
- ☐ Declined to answer

Height in cms:

Weight in kg:

Occupation:

Workload:

- ☐ sedentary
- ☐ manual (above shoulder height)
- ☐ manual (below shoulder height)

Mechanism of injury

- ☐ Sport
- ☐ Assault
- ☐ Falls
- ☐ MVA/Other

Sport played:

Type:

- ☐ Organized officiated Contact sport
- ☐ Informal non-officiated contact sport
- ☐ Organized officiated overhead sport
- ☐ Informal non-officiated overhead sport
- ☐ Organized officiated collision sport
- ☐ Informal non-officiated collision sport
- ☐ Not involved in contact/collision sport
- ☐ Not involved in overhead sport

Level of play:

- ☐ Recreational
- ☐ competitive
- ☐ Elite

Are you back to playing your sport?

☐ Yes
☐ No

Time to return to sport after shoulder surgery:

Hand Dominance

☐ Right
☐ Left

Dominant limb (arm used for throwing):

☐ Right
☐ Left

Affected shoulder

☐ Right
☐ Left

Date of first traumatic anterior dislocation/subluxation:

Number of dislocations/subluxations after the initial injury:

Was your shoulder immobilized after the injury

☐ Yes
☐ No

Period of immobilization:

Have you had shoulder surgery

☐ Yes
☐ No

If 'yes' date of surgery:

Physiotherapy treatment:

Pre-surgery

☐ Yes
☐ No

Number of physiotherapy treatments:

Post-surgery

☐ Yes
☐ No

Number of post-surgery physiotherapy treatments:

Appendix F: The Western Ontario Shoulder Instability

The Western Ontario Shoulder Instability Index (WOSI)

Clinician's name (or ref) .... **Patient's name (or ref)** ....

The following questions concern the symptoms you have experienced due to your shoulder problem. In all cases, please enter the amount of the symptom you have experienced in the last week. (please move the slider on the horizontal line.)

1. How much pain do you experience in your shoulder with overhead activities?

No pain — Extreme pain

2. How much aching or throbbing do you experience in your shoulder?

No aching/throbbing — Extreme aching/throbbing

3. How much weakness or lack of strength do you experience in your shoulder?

No weakness — Extreme weakness

4. How much fatigue or lack of stamina do you experience in your shoulder?

No fatigue — Extreme fatigue

5. How much clicking, cracking or snapping do you experience in your shoulder?

No clicking — Extreme clicking

6. How much stiffness do you experience in your shoulder?

No stiffness — Extreme stiffness

12. How much has your shoulder affected your ability to perform the specific skills required for your sport or work? (If your shoulder affects both sports and work, consider the area that is most affected.)

Not affected — Extremely affected

13. How much do you feel the need to protect your arm during activities?

Not at all — Extreme

14. How much difficulty do you experience lifting heavy objects below shoulder level

No difficulty — Extreme difficulty

15. How much fear do you have of falling on your shoulder?

No fear — Extreme fear

16. How much difficulty do you experience maintaining your desired level of fitness

No difficulty — Extreme difficulty

17. How much difficulty do you have “roughhousing” or “horsing around” with family or friends

No difficulty — Extreme difficulty

7. How much discomfort do you experience in your neck muscles as a result of your shoulder?

No discomfort — Extreme discomfort

8. How much feeling of instability or looseness do you experience in your shoulder?

No instability — Extreme instability

9. How much do your compensate for your shoulder with other muscles?

Not at all — Extreme

10. How much loss of range of motion do you have in your shoulder?

No loss — Extreme loss

11. How much has your shoulder limited the amount you can participate in sports or recreational activities?

Not limited — Extremely limited

18. How much difficulty do you have sleeping because of your shoulder

No difficulty — Extreme difficulty

19. How conscious are you of your shoulder

Not conscious — Extremely conscious

20. How concerned are you about your shoulder becoming worse

No concern — Extremely concerned

21. How much frustration do you feel because of your shoulder

No frustration — Extremely frustrated

Physical symptoms Score is: 0 / 0 %

Sports/recreation/work Score is: 0 / 0 %

Lifestyle Score is: 0 / 0 %

Emotion Score is: 0 / 0 %

The WOSI Score is: 0 / 0 %

Link for Reference: The Development and Evaluation of a Disease-Specific Quality of Life Measurement Tool for Shoulder Instability
The Western Ontario Shoulder Instability Index (WOSI)Am J Sports Med November 1998 vol. 26 no. 6 764-772
Alexandra Kirkley, MD, FRCSC*, Sharon Griffin, CSS, Heidi McLintock, BSc, PT, MSc and, Linda Ng, BSc, PT,
http://ajs.sagepub.com/content/26/6/764.abstract

Appendix G: The Rowe Score for Instability

The Rowe Score for Instability

(With the permission of the Journal of Bone & Joint Surgery)

Clinician's name (or ref) ____ Patient's name (or ref) ____

Please answer the following questions.

Section 1 - Stability	
○	No Recurrence, subluxation or apprehension
○	Apprehension when placing arm in certain positions
○	Subluxation (not requiring reduction)
○	Recurrent Dislocation

Section 2 - Motion	
○	100% of normal ext rotation, int rotation and elevation
○	75% of normal ext rotation, int rotation and elevation
○	50% of normal ext rotation, int rotation and elevation
○	50% of normal elevation, and int rotation, No ext rotation

Section 3 - Function	
○	No limitation of work or sports, little or no discomfort (eg shoulder strong overhead, lifting, swimming, throwing, tennis)
○	Mild limitation and minimum discomfort
○	Moderate limitation and discomfort
○	Marked limitation and pain

Appendix H: Shoulder Instability Return to Sport after Injury (SI-RSI) Scale

Shoulder Instability Return to Sport after Injury (SI-RSI) SCALE

Instructions:

Please answer the following questions referring to your main sport prior to injury. For each question tick a box ☑ between the two descriptions to indicate how you are feeling right now relative to the two extremes.

1. Are you confident that you can perform at your previous level of sport participation?

Not at all	0	1	2	3	4	5	6	7	8	9	10	Fully
Confident	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Confident

2. Do you think you are likely to re-injure your shoulder by participating in your sport?

Extremely	0	1	2	3	4	5	6	7	8	9	10	Not likely
likely	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	at all

3. Are you nervous about playing your sport?

Extremely	0	1	2	3	4	5	6	7	8	9	10	Not nervous
nervous	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	at all

4. Are you confident that your shoulder will be stable during playing your sport?

Not at all	0	1	2	3	4	5	6	7	8	9	10	Fully
confident	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	confident

5. Are you confident that you could play your sport without concern for your shoulder?

Not at all	0	1	2	3	4	5	6	7	8	9	10	Fully
confident	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	confident

6. Do you find it frustrating to have to consider your shoulder with respect to your sport?

Extremely	0	1	2	3	4	5	6	7	8	9	10	Not at all
frustrating	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	frustrating

7. Are you fearful of re-injuring your shoulder by playing your sport?

Extremely	0	1	2	3	4	5	6	7	8	9	10	No fear
fearful	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	at all

8. Are you confident about your shoulder holding up under pressure?

Not at all	0	1	2	3	4	5	6	7	8	9	10	Fully
confident	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	confident

9. Are you afraid of accidentally injuring your shoulder by playing your sport?

Extremely	0	1	2	3	4	5	6	7	8	9	10	Not at all
afraid	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	afraid

10. Do you have thoughts of having to go through surgery and rehabilitation again prevent you from playing your sport?

All of the time	0 ☐	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐	6 ☐	7 ☐	8 ☐	9 ☐	10 ☐	None of the time

11. Are you confident about your ability to perform well at your sport?

Not at all confident	0 ☐	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐	6 ☐	7 ☐	8 ☐	9 ☐	10 ☐	Fully confident

12. Do you feel relaxed about playing your sport?

Not at all relaxed	0 ☐	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐	6 ☐	7 ☐	8 ☐	9 ☐	10 ☐	Fully relaxed

SIRSI score (Total x 100) / 120 = %

Appendix I: Tampa Scale for Kinesiophobia

Tampa Scale for Kinesiophobia

(Miller , Kori and Todd 1991)

1 = strongly disagree
2 = disagree
3 = agree
4 = strongly agree

1. I'm afraid that I might injury myself if I exercise	1	2	3	4
2. If I were to try to overcome it, my pain would increase	1	2	3	4
3. My body is telling me I have something dangerously wrong	1	2	3	4
4. My pain would probably be relieved if I were to exercise	1	2	3	4
5. People aren't taking my medical condition seriously enough	1	2	3	4
6. My accident has put my body at risk for the rest of my life	1	2	3	4
7. Pain always means I have injured my body	1	2	3	4
8. Just because something aggravates my pain does not mean it is dangerous	1	2	3	4
9. I am afraid that I might injure myself accidentally	1	2	3	4
10. Simply being careful that I do not make any unnecessary movements is the safest thing I can do to prevent my pain from worsening	1	2	3	4
11. I wouldn't have this much pain if there weren't something potentially dangerous going on in my body	1	2	3	4
12. Although my condition is painful, I would be better off if I were physically active	1	2	3	4
13. Pain lets me know when to stop exercising so that I don't injure myself	1	2	3	4
14. It's really not safe for a person with a condition like mine to be physically active	1	2	3	4
15. I can't do all the things normal people do because it's too easy for me to get injured	1	2	3	4
16. Even though something is causing me a lot of pain, I don't think it's actually dangerous	1	2	3	4
17. No one should have to exercise when he/she is in pain	1	2	3	4

Reprinted from:
Pain, Fear of movement/(re) injury in chronic low back pain and its relation to behavioral performance, 62, Vlaeyen, J., Kole-Snijders A., Boeren R., van Eek H., 371.

Scoring Information
Tampa Scale for Kinesiophobia
(Miller et al 1991)

A total score is calculated after inversion of the individual scores of items 4, 8, 12 and 16.