Shoulder Proprioception and Motor Control

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ABSTRACT

The shoulder is an inherently unstable joint and requires well-coordinated muscle work and an appropriate sensorimotor system for it to remain stable. The sensorimotor system is defined as all the sensory, motor, central integration and processing components involved in maintaining joint stability. Shoulder action involving overhead work places great demands on the shoulder joint and can result in shoulder lesions, such as impingement syndrome. Moreover, activities requiring repetitive arm movements, including high velocity actions, have also been identified as a risk factor for shoulder impingement. Within the literature there is a notional link suggested between this condition and neuromuscular alterations with proprioceptive loss, however scientific exploration of such hypothesis has not yet been fully explored.

The aims of the study are to establish normal patterns of proprioception in the shoulder and to establish what the normal patterns of shoulder motor control are. To achieve this, several studies to test reliability and validity of the protocols to measure surface electromyographic activity (sEMG), joint positional sense and force reaction of the shoulder were developed.

32 participants agreed to take part in a body of work to explore measurement of positional sense, in which the ability to replicate three criterion positions (0º, 45º and 80º of shoulder rotation) were investigated. 26 participants agreed to take part in a study to measure force reaction, in which the ability to produce a predetermined amount of force was studied. Both positional sense and force reaction (proprioceptive skills) were measured using an isokinetic dynamometer device. A third study, with 14 participants, was undertaken to measure the electromyographic activity during the movement of shoulder abduction and a volleyball throwing specific task.

For positional sense measurement, there were no significant differences between criterion angles/positions and between trials ($p>0.05$). However, the relative reliability indicated poor to fair agreement (ICC between 0.14 and 0.38) and repeatability was poor (Bland &Altman between 14.49º and 18.31º). This may have been due to absence of variability in the data and the nature of the unconstrained movement. The force

reaction study indicated that the participants underestimated the target. Moreover the amount of errors decreased in relation to the increase in the angle of external rotation (p=0.001). This was the opposite for internal rotation (p=0.017). The ICC results were excellent (ranged between 0.75 and 0.87) and internal rotation (middle range) measurements demonstrated better coefficients of repeatability (between 1.42 and 2.61N.m.). The study investigating timing of shoulder muscle onset indicated that there were no differences between trials (p>0.05), with exception of the clavicular portion of the pectoralis muscle, during abduction in the scapular plane movement (p=0.046). There was also pre-activation of all portions of the deltoid muscle and infraspinatus in both movements. The serratus anterior muscle and supraspinatus were also preactivated during abduction in the scapular plane. While relative coefficients of reliability ranged from poor to Excellent (ICC between 0.05 and 0.79), repeatability values were good for the prime movers, suggesting that small changes can be interpreted as meaningful changes. On the contrary, changes in muscle onset timing of muscles that were neither agonists nor synergists for the desired movement were more variable.

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DECLARATION

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

Sandra Rodrigues

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CHAPTER I: INTRODUCTION

1.1 INTRODUCTION

The clinical rationale for this study was to explore the possible differences in shoulder proprioception and motor control in patients with shoulder impingement syndrome, a condition known as SIS, when compared to normal participants. However, in order to be able to do this, a measurement protocol needed to be designed and tested to ensure that the measurements demonstrated sufficient reliability and validity and this constitutes the focus for the present research.

Providing the protocol demonstrate adequate levels of reliability and validity within normal participants, then the second phase of the study would be to test the protocol in participants demonstrating symptoms of SIS.

The review of the literature, to support this programme of research involved applying most of the principles of systematic reviews, including systematic and explicit methods to identify, select and critically appraise relevant primary research (Khan et al., 2001, Law and MacDermid, 2008).

The aim of the study was to explore the development of the measurement protocols that are reliable and valid in the measurement of proprioception and motor control at the shoulder.

Studies involving EMG which were to be included in the literature review were found using the following search terms and data bases: Medline, Cinahl, SPORDiscus and PEDro were searched from their inception to April 2016, using the key-words: “onset, timing, EMG, electromyography, overhead, volleyball, subacromial impingement syndrome, SIS, shoulder” and boolean operators (AND, OR). Filters for English language, peer-reviewed studies and human subjects were also applied. Citation tracking and reference scanning of the bibliographies of all included studies were undertaken to identify any further relevant trials not captured by the initial search. A set of inclusion criteria were established prior to searching. These were: humans as participants, English language, electromyographic recording of muscle onset timing as an outcome measure, movements of elevation and depression of the shoulder in the sagittal, coronal or scapular plane, in an upright position, or an unconstrained volleyball throwing technique.

Other techniques have been described to identify muscle activation, namely phase contrast magnetic resonance imaging and real-time ultrasound (Wen et al., 2008, Finni et al., 2006, Van et al., 2006) however, they do not currently have the ability to measure the small changes in timing accurately (Crow et al., 2011). Therefore studies using these outcomes measures were excluded.

Studies that measured people with neurological conditions, orthopedic pathological conditions other than SIS, constrained movements, systematic reviews or which topic did not match the aim of this review were also excluded. Studies of pathological conditions other than SIS, but with control group, were eligible for inclusion but only with the information from the “normal” group. The also applied to studies with sports practice other than volleyball, but with control group.

Studies involving isokinetic dynamometry (IKD) which were to be included in the literature review were found using the following search terms and data bases: Medline, Cinahl, SPORDiscus and PEDro were searched from their inception to April, 2016, using the key-words “shoulder proprioception, isokinetic, IKD, overhead, volleyball, subacromial impingement syndrome, SIS, shoulder” and Boolean operators (AND, OR). Filters for English language, peer-reviewed studies and human subjects were also applied. Citation tracking and reference scanning of the bibliographies of all included studies were undertaken to identify any further relevant trials not captured by the initial search. A set of inclusion and exclusion criteria was established prior to searching. Inclusion criteria were humans as participants, English language, proprioceptive analysis of shoulder measured by the isokinetic machine as the outcome measure and an active reposition sense protocol.

Other techniques have been described to characterize proprioception, namely histological and neurophysiological (Jerosch and Prymka, 1996). The clinical setup of the isokinetic machine has been referred as being a reliable way to measure several aspects of the shoulder proprioception (Dover and Powers, 2003). The IKD has also been referred as the gold standard even for handheld dynamometry comparison (May et al., 1997). Studies using outcome measures other than IKD were excluded.

Studies that measured people with neurological conditions, orthopedic pathological conditions other than SIS, studies that did not use the IKD machine, systematic reviews or which topic did not match the aim of this review were also excluded. Studies of pathological conditions other than SIS, but with control group, were eligible for inclusion but only with the information from the “normal” group. The same applied to studies with sports practice other than volleyball, but with control group. Studies with reference to both active and passive joint positional sense evaluation were eligible for inclusion but only the active information was taken into account.

The methodological quality of the included studies was evaluated using the STROBE checklist (von Elm et al., 2007). This is validated for assessment of the methodological rigor of observational studies. The CASP checklist for randomized controlled trials and case control studies (CASP, 2014) were also used where appropriate.

This chapter describes the anatomical and kinesiological features of the shoulder and its inherently unstable identity, which may contribute to the development of injury, with proprioceptive loss and neurophysiological alterations.

1.2 RATIONALE FOR STUDY

The shoulder joint is particularly susceptible to injuries because of its great mobility and inherent instability. The heavy reliance on soft tissue structures and balanced muscular control for stabilizing through a large range of motion places considerable demands on these structures, resulting in both acute and chronic injuries (Shultz et al., 2010). In fact, shoulder problems are a significant cause of morbidity and disability in the general population, representing an important economic burden (Walker-Bone et al., 2004).

Patients visiting their general practitioner with complaints of the arm, neck and/or shoulder (CANS) (Huisstede et al., 2007), that is, non-traumatic musculoskeletal complaints of the upper extremity not caused by any systemic disease, frequently report shoulder complaints. Of these, 33% are diagnosed with SIS, also identified as shoulder impingement syndrome or SIS (Feleus et al., 2008). Earlier research suggested that the shoulder impingement syndrome was the most frequently recorded disorder (41% of all patients) in Dutch general practice (Van der Windt et al., 1995).

Moreover, shoulder disability results in major impact on the lives of many sports players and workers, being one of the most prevalent shoulder condition, affecting 1 in 3 adults at some point in their lives (Roddy et al., 2014). A recent longitudinal study of 37402 participants suggested that highly repetitive work, with arm elevation above 90º, for more than 3hours/day entailed an approximately doubled risk of surgery for SIS (Svendsen et al., 2013). The findings also suggested that people engaged in forceful repetitive work, with arms elevated are an at risk group for whom interventions are indicated in order to prevent surgery. Excessive or repetitive activities may therefore precipitate a localized tendinopathy and rotator cuff degeneration or tears, that inevitably compromise the function of the tendon in stabilizing and depressing the humeral head (Linaker and Walker-Bone, 2015). Such damage to the shoulder can result in pain, which is the commonest of musculoskeletal symptoms and a lifetime prevalence of up to 66.7% (Luime et al., 2004).

Stability is therefore reliant upon a functional system of musculo-tendinous support both within (the rotator cuff) and outside of the joint capsule. However, its complex design leaves it prone to injury and sprain/strain, particularly when it is excessively overloaded (Linaker and Walker-Bone, 2015).

Shoulder complaints with clinical findings presumed to originate from subacromial structures when elevating the arm have been classified as SIS, including the rotator cuff syndrome, tendinosis of the infraspinatus, supraspinatus and subscapularis muscle, and bursitis in the shoulder area (Huisstede et al., 2007, Gebremariam et al., 2011). Severini et al. (2014), also described the same implications on the long head of biceps and the shoulder capsule. Additionally it was suggested that this encroachment results in shoulder pain, exacerbated by forward elevation and rotation of the upper extremity.

There is evidence that altered patterns of upward rotation of the scapula may contribute to shoulder problems. The dynamics of scapular muscles are very important to enable optimal positioning of the scapula and prevent shoulder injuries. Although the scapular dynamics have been well explored (Borstad and Ludewig, 2002, Ludewig and Cook, 2000a, Ludewig and Reynolds, 2009), a recent systematic review of the literature, by Struyf et al. (2014), fails to identify an established consensus on muscle scapular recruitment timing on patients with SIS. Moreover, the implications of the repetitive, overhead and sometimes, high velocity movements such as in overhead activities and sports, on the glenohumeral muscles, have not been fully explored and needs further investigation. There is also evidence that alteration of the subacromial space may be caused by translation of the humeral head instead of solely alteration of scapular position, as previously thought (Graichen et al., 2005).

The timing of muscle activation during elevation in the sagittal plane in participants with SIS appears to be delayed significantly only in serratus anterior muscle (Worsley et al., 2013). However, during the abduction in the frontal plane, in SIS, the timing of muscle activation has been shown to be delayed in both serratus anterior and lower trapezius (Worsley et al., 2013). To date, this is the only study of pathological conditions to include measurement in both sagittal and frontal plane elevation. Thus comparison to other studies is not possible. Early work by Wadsworth and Bullock-Saxton (1997), suggest that elevation in the scapular plane, also described as scaption, in SIS, is delayed in lower trapezius. These findings were more recently endorsed by Worsley et al. (2013). However, conversely, no differences in neuromuscular activity of trapezius and serratus anterior were found between participants with SIS and asymptomatic participants (Larsen et al., 2013, Moraes et al., 2008). The topic therefore remains controversial and open to further exploration.

The evidence reported within literature is therefore equivocal and incomplete regarding motor control strategies in patients with SIS. The literature also suggests the need for more studies to help enhance the knowledge about the adaptive strategies presented by these patients. A systematic review of the reported studies indicate of fair to low quality, with only two stating subject selection criteria – convenience sample (Larsen et al., 2013, Wadsworth and Bullock-Saxton, 1997), none of the studies justified sample size, nor referred to measurement of reliability and all the studies failed to detail whether testers were blind to the group allocation. Conversely, all the studies were control matched. Different methods of determining sEMG onset were used in these studies, including visual inspection (Worsley et al., 2013, Larsen et al., 2013), 2 SD above mean with stability of 50 ms (Moraes et al., 2008) and a percentage (5%) of sEMG trace maximum amplitude (Wadsworth and Bullock-Saxton, 1997) and no consensus could be made regarding the preferred method to determine EMG onset and more studies are needed in this field of research.

Early work by Wadsworth and Bullock-Saxton (1997), and more recent work by Moraes et al. (2008), reports greater variability in muscle onset for participants with SIS, which may be due to the use of small sample sizes in the studies. A larger sample size, determined using a power calculation, would be required to provide adequate power to detect true differences and it was not the case of the above mentioned studies. Moreover, most of the evidence is based on measurement of trapezius and serratus anterior muscles. Broadening the range of muscles investigated around the shoulder joint, would also add the current body of knowledge.

Roy et al. (2008), developed a well-designed cross-sectional observational study, with valid results. However, limitations of the paper included the absence of sample size power calculation and blinding of either the participants or the investigator. Nonetheless, they did address potential sources of bias. Their findings reported altered motor strategies during reaching tasks, in SIS patients. However, not all individuals with shoulder impingement present the same abnormal motor strategy. Therefore, characterizing motor strategies before implementing rehabilitation intervention is essential.

To date there have only been two scientifically robust studies (Cools et al., 2003, Wadsworth and Bullock-Saxton, 1997) that have suggested that changes in motor control occurs in both the affected and the unaffected shoulder in SIS patients. This infers that there may be a more global response associated with the condition, instead of the local emphasis that SIS has historically received, however this has yet to be confirmed.

All the studies reported thus far, have not reported the presence or absence of pain during data collection. It is known that pain may also affect muscle control (Hodges and Moseley, 2003, Hess et al., 2005, MacDonald et al., 2009), mostly because nociceptive input may influence peripheral and central motor control. Hess et al. (2005), advocate that the subscapularis onset, in a task of rapid external rotation movements, tends to be significantly delayed in the presence of pain. These patients with SIS have been described as having altered motor strategies of the scapular muscles, which might be explained by either the under acromial compression of the structures and/or pain. However these findings need further validation.

Proprioceptive feedback, has also been suggested as being altered in these patients. When the sensorimotor system fails and injury occurs, the result is mechanical instability and further altered sensorimotor system leading to functional instability. This mechanism might contribute to repeated injury. The sensorimotor alteration occurs because many of the mechanical restraints of the joint are mechanoreceptors which contribute to proprioceptive information (Myers et al., 2006).

Bandholm et al. (2006), observed that patients with SIS have impaired kinesthesia of the affected shoulder during slow passive shoulder abduction. This suggests that they have altered shoulder afferent feedback mechanisms or altered central processing of afferent input. A more recent study by Maenhout et al. (2012), has described that patients overestimate the target during force reproduction tests. Although the study was performed on patients with rotator cuff tendinopathy, it is a condition that has been related to impingement.

Conversely, Haik et al. (2013), suggests that joint positional sense is not altered in workers with SIS. His study explored asymptomatic female assembly line workers exposed to overhead repetitive activities. This study raises the question of whether SIS patients have developed new proprioceptive strategies following shoulder injury, while asymptomatic overhead workers, with decreased JPS, are under the risk of pathology development, such as SIS.

In summary, the evidence explored in this literature review is equivocal. Some author suggests that SIS patients have altered shoulder afferent feedback (Myers and Lephart, 2000, Bandholm et al., 2006), whilst other authors such as Haik et al. (2013), do not support these claims and the topic remains controversial.

Furthermore, treatment of patients with impingement symptoms commonly includes exercise intended to restore "normal" movement patterns (Ludewig and Cook, 2000a). There is currently no agreement in the literature that defines what the normal movement pattern are nor muscle activity sequencing (Wattanaprakornkul et al., 2011, Rajaratnam et al., 2013, Reed et al., 2013b, Wickham et al., 2010, Szucs and Borstad, 2013, Seitz and Uhl, 2012b). This further supports the need and the importance of studying individuals without pathology. Moreover, although several therapeutic approaches have been advocated to correct any asynchronous muscle activity, "there is however, a lack of cohesive evidence to determine which specific muscles should be targeted during rehabilitation" (Chester et al., 2010). Therefore more studies that enhance the understanding of its mechanisms are needed.

It is hypothesized that a failing of the upper limb motor program may lead to pathology and shoulder pathology which in turn may lead to motor program alterations. Moreover, it could be hypothesized that impingement may lead to lesion of the subacromial muscles, leading to altered motor strategies and decreased proprioception. Alternatively, the over stimulated rotator cuff presented in overhead work, leads to altered motor control and consequently altered proprioceptive feedback. However, an alternate hypothesis is that SIS patients could have developed new proprioceptive strategies, but all of these issues need confirmation.

There is also a need to determine if these described motor patterns are representative of the entire population of SIS or is it specific of sub-groups and whether the presence of a more global response, instead of a unilateral shoulder localized condition, which also needs clarification.

1.3 OUTLINE OF THE THESIS

From the review of the literature, it is unclear whether the existence of altered shoulder proprioception and motor control leads to impingement syndrome or whether it is the impingement syndrome that leads to decreased shoulder proprioception and altered motor control. Since both aspects need to be explored fully, this study will focus on exploring shoulder proprioception and motor control in shoulder motion. The research under investigation will explore the development of measurement protocols that are reliable and valid in the measurement of proprioception and motor control at the shoulder.

The aims of the study were:

1. To establish normal patterns of proprioception in the shoulder
2. To establish normal patterns of shoulder motor control

The objectives of the study were:

I. To develop reliable methods to accurately measure proprioception of the shoulder joint
II. To measure the natural variance in the proprioceptive performance
III. To develop reliable methods to measure shoulder motor control
IV. To validate the methods designed to measure motor control
V. To measure the natural variance in shoulder motor control

The thesis consists of 6 chapters. Chapter two reviews the relevant shoulder anatomy and pathology, chapter three analyses the theoretical concepts related to the sensorimotor system, namely proprioception and motor control, which is the focus of the later investigations. It will discuss the influence of numerous aspects, such as the sports practice and overhead work on the sensorimotor system. Chapter four considers the potential pathogenesis of the shoulder pathology, culminating in the review of the latest evidence on shoulder impingement syndrome. Chapter five describes the rationale for the experimental works, exploring the use of sEMG and isokinetic evaluation of proprioceptive skills and the results of the two studies in the fields of shoulder proprioception and motor control are presented and discussed. Chapter six contains the general discussion and overall conclusions and direction for future research.

CHAPTER II: NORMAL SHOULDER ANATOMY AND PATHOLOGY

2.1 INTRODUCTION

The shoulder complex allows a large range of motion to occur. It ultimately enables the upper extremity to be positioned to allow the hand to function (Myers and Lephart, 2000, Veeger and van der Helm, 2007). The movements involved include movements of the glenohumeral, acromioclavicular, sternoclavicular and scapulothoracic joints, which in turn enable accurate positioning of the limb to carry out precise motor activities (Donnelly et al., 2013).

Even though the shoulder has a high degree of mobility it is an inherently unstable joint (Chang et al., 2006), it can be seen as a perfect compromise between mobility and stability (Myers and Lephart, 2000, Veeger and van der Helm, 2007). Shoulder support, stability and integrity is only possible by virtue of its passive (mechanical) and dynamic restraints. Mechanical restraints include the glenohumeral joint capsule, glenohumeral and extracapsular ligaments, glenoid labrum, bony geometry and intraarticular pressure. The dynamic restraints results from activation and force production by the muscles surrounding the shoulder (Myers et al., 2006, Magee, 2008). The rotator cuff provides the main stabilizing structure for the glenohumeral joint and is composed of the supraspinatus, infraspinatus, subscapularis and teres minor muscles (Donnelly et al., 2013).

In di-arthrodial joints such as the glenohumeral (GH) joint, a large range of mobility can only be obtained if one of the articular surfaces is considerably smaller than the other, which directly affects joint stability (Myers and Lephart, 2000, Veeger and van der Helm, 2007). To improve joint stability, the joint translations should be constrained, either by compressing the head in the socket in a spherical joint such as the glenohumeral joint, or by ligamentous structures in other joint types. If large translational forces, in parallel to the articular surfaces occur, these forces must be counteracted by ligaments or stabilizing muscle activity, redirecting the joint reaction force (JRF) towards the articular surface (Veeger and van der Helm, 2007). This interaction between the static (passive) and dynamic (active) components of functional stability is mediated by the sensorimotor system (Myers and Lephart, 2000, Magee, 2008, Myers et al., 2006), which will be further discussed in chapter III.

2.2 PASSIVE STABILIZING MECHANISMS

The cartilaginous glenoid labrum covers the edges of the glenoid fossa, cushioning the glenohumeral joint, while the ligaments of the shoulder girdle lies at varying angles to limit movement in multiple directions. Several ligaments stabilize the shoulder (sternoclavicular ligament, coracohumeral ligament and the coracoclavicular ligaments). However, it is the coracoacromial ligament, a v-shaped structure that connects the scapula's coracoid and acromion processes to stabilizes the humeral head during overhead movements, preventing superior glide and the glenohumeral ligaments, that isolated or synergically help hold the proximal humerus in the glenoid fossa of the scapula (Cael, 2012). Felli et al. (2012), in a study involving cadaveric samples noted that the resistance, of the superior, middle and inferior glenohumeral ligament, increases in value for angles between 45º and 90º of abduction. They also noticed that the resistance further increased with addition of external rotation, indicating the important stabilizing function of this ligaments in those positions (Felli et al., 2012). The contribution of the inferior glenohumeral ligament is negligible in positions of neutral adduction and adduction in external rotation, representing the limited function of these ligaments for middle range and the importance for end of range dynamic joint stability. The purpose of Felli' study was to evaluate the function of the three glenohumeral ligaments in both the static and dynamic humeral phases by analyzing the time of major stabilizing activity, expressed by the level of tensioning, in different positions. Electrical impedance of current was measured using a tetrapolar detection system. The specimens were described as "fresh", however time since death was not noted and major muscles around the shoulder have been sectioned to prevent their stabilizing action.

2.3 MUSCLES AROUND THE GLENOHUMERAL JOINT AND ACTIVE STABILIZING MECHANISMS

When the arm is raised, there is a generally accepted pattern of motion at the shoulder: The scapula upwardly rotates, decreases its internal rotation and posteriorly tilts (Ludewig et al., 1996, Ebaugh et al., 2006) and the humerus elevates and externally rotates (Ludewig and Cook, 2000b, Ebaugh et al., 2006). However the normal motor control strategies to perform that action are still under debate.

In fact, there is no consistency in the order of activation found by different research papers in asymptomatic groups. When the normal movement of flexion is performed in the sagittal plane, it starts with a simultaneous pre-activation of both supraspinatus and deltoid anterior. With the addition of an external load the infraspinatus becomes active at the same time as the others and prior to movement (Wattanaprakornkul et al., 2011). However Rajaratnam et al. (2013), suggested that the order was not quite the same, with preactivation of only the ipsilateral upper trapezius, then (post activation) of posterior deltoid, supraspinatus, teres major and infraspinatus.

Abduction in the frontal/coronal plane seems to present a preactivation of the ipsilateral upper trapezius, followed by a post-activation of the posterior deltoid, supraspinatus, teres major and infraspinatus (Rajaratnam et al., 2013). For Reed (2013b), there seems to be a major pre-activation of supraspinatus, subscapularis, serratus anterior, lower trapezius and infraspinatus, as well as for the upper trapezius and middle deltoid. Furthermore, there weren’t any differences between loaded and unloaded positions or even between the coronal and the scapular plane. For the same movement, however, Wickham et al. (2010) suggest preactivation (in order) of supraspinatus, middle trapezius and middle deltoid and post activation of serratus anterior, upper trapezius, rhomboids, anterior deltoid, posterior deltoid, lower trapezius, infraspinatus, latissimus dorsi, upper subscapularis, pectoralis minor and finally the major.

When movements were performed in the scapular plane, 30º anterior to the coronal plane, normal participants presented pre-activation of all the muscles (supraspinatus, subscapularis, serratus anterior, lower trapezius, infraspinatus, upper trapezius and middle deltoid) (Reed et al., 2013b). However they did not report the reliability of the method, and they have chosen an onset detection algorithm of 3 standard deviations above the mean, what might have been a matter of criticism when evaluating functional movements, the addition of a dumbbell makes the 3 standard deviations criteria suitable for onset identification, mostly because the amount of the required muscle activity to elevate the load is bigger. Another investigation, from the same year, using 40º anterior to the coronal plane as a reference for the scapular plane, have found that the upper trapezius muscle onset happened statistically later in females, for the descending aspect of the trapezius muscle (Szucs and Borstad, 2013). Although reliability of the method was not reported, onset was identified using Matlab algorithm, with the criteria of 2 standard deviations above the mean. Nevertheless, the chosen reference for the identification of the onsets was the activation of the anterior deltoid muscle, and perhaps middle deltoid might have been also considered as prime mover.

Other important issues to consider regarding the interpretation of EMG onset activity, are the differences in methodologies employed, which made comparison difficult. For example, there have been a range of standard deviations around the mean reported (Wattanaprakornkul et al., 2011, O'Connell et al., 2006, Szucs and Borstad, 2013) and also a range of percentage of the maximum voluntary contraction (Seitz and Uhl, 2012a).

Overall, the literature reports wide variation of muscle combinations and movements and few studies have investigated the same muscles for the same task. The various methodologies employed greatly contribute to the lack of consistent findings reported within the literature.

Moreover, the pathological conditions of the shoulder may also impair this motor program. This may therefore produce subtle compensatory changes in the normal motor control exerted during the upper limb movements, especially those involving rapid and overhead actions (Severini et al., 2014).

Falworth and Lambert (2007), suggested that during shoulder flexion and abduction, deltoid and supraspinatus muscles work together producing vertical shear force. Although this is not completely true, since the vertical shear force produced by the deltoid is mediated by the supraspinatus (de Witte et al., 2014, Reed et al., 2013a), it is thought that this movement, if performed in a cuff-deficient shoulder, may lead to superior migration of the humeral head due to the unopposed action of deltoid. Furthermore, subscapularis, teres minor, infraspinatus, supraspinatus and long head of biceps must force the humeral head firmly into the glenoid fossa in order to minimize humeral head translation, in normal shoulders. This acquisition of movement patterns developed over a long period, as the body adapts to new and repeated stimuli, is presented by Scibek et al. (2009). It is hypothesized that altered movement pattern of the glenohumeral muscles may lead to injury.

Early work modeling the rotator cuff and deltoid muscle forces, demonstrated the importance of the muscular force couple to center the humeral head during elevation of the arm (Payne et al., 1997). The inferior forces of the infraspinatus, teres minor, and subscapularis muscles were necessary to neutralize the superior shear force produced by the deltoid and supraspinatus muscles, which was proposed earlier by Kapandji (1982).

Supraspinatus, in conjunction with infraspinatus, teres minor and subscapularis function as a unit to stabilize the humeral head in the glenoid fossa. Specifically, the supraspinatus depresses the humerus as prime movers (such as deltoid muscle) and moves the shoulder through abduction. Infraspinatus works with teres minor to position the humeral head posteriorly in the glenoid fossa and prevent impingement on the coracoid process of the scapula. Infraspinatus is one of the most powerful external rotators and it works with teres minor for movements like pitching and hitting overhead. It is also recruited eccentrically, to slow the upper extremity, during the follow-through or deceleration phase of these movements. Teres minor also assists in lowering the raised arm along with teres major, latissimus dorsi and costal fibres of the pectoralis major, which contributes to proper mechanics for complex movements such as throwing and hitting from overhead. Subscapularis stabilizes the humeral head during the movements of the pectoralis major, latissimus dorsi, teres major and anterior deltoid as they lower the raised arm downward during pulling movements, such as throwing and hitting overhead (Cael, 2012).

Following the work of Kapandji (1982), the role of the long head of biceps on shoulder coaptation, for shoulder physiology and stability, has been described. In neutral rotation or external rotation, the efficacy of the long head of biceps is maximal. During shoulder abduction, the shorter head elevates the humerus in relation to the scapula, avoiding the inferior luxation of the humeral head. Concomitantly, the long head coapts the humeral head in the glenoid fossa.

According to Falworth and Lambert (2007), during shoulder flexion and abduction, deltoid produces vertical shear force. This movement, if performed in a cuff-deficient shoulder, leads to superior migration of the humeral head. Furthermore, subscapularis, teres minor, infraspinatus, supraspinatus and long head of biceps must therefore force the humeral head firmly into the glenoid fossa in order to minimize humeral head translation.

Muscle strength balance is vital to dynamically stabilizing the glenohumeral joint throughout the entire range of arm motion, accurately positioning the glenoid and humerus to confer ball and socket kinematics, and stabilizing the scapula on the trunk as a stable base for arm action. Force couples including anterior/posterior rotator cuff activation compresses the humeral head into the glenoid fossa, the rotator cuff/deltoid stabilizes the moving arm into the socket, and upper trapezius/lower trapezius: serratus anterior positions and stabilizes the scapula (Kibler et al., 2014).

The mechanism by which the rotator cuff maintains the humeral head in the glenoid fossa is known as concavity-compression and it is this stabilizing mechanism that allows for the glenohumeral joint to resist shear forces.(Ahmad et al., 2014).

It has generally been accepted that the synergy of the rotator cuff and the deltoid is required for strong shoulder abduction. When the humerus is at 0º of abduction, the deltoid’s force of action is nearly vertical. This isolated force would cause upward translation of the humerus and impingement of the soft tissue. Thus, the role of the supraspinatus muscle is to assist abduction till 90º and to stabilize the humerus (Ahmad et al., 2014). However the role of supraspinatus is still not clear, since it has been referred as active during abduction but not prior to other common abductors (Reed et al., 2013a). The infraspinatus, subscapularis and teres minor pull the humerus at the glenoid in a downward direction, which work to compress the humeral head and counterbalance the upward force produced by the deltoid. At 0º of abduction, the subscapularis is largely responsible for shoulder joint stabilization (force coupling), with smaller contributions from the infraspinatus and teres minor. At end-range, the contribution of subscapularis decline, but the contribution from the infraspinatus continues to rise (Ahmad et al., 2014).

Ahmad et al. (2014), also suggests that the specific positioning of the scapula, between 30 to 40º anterior to the coronal plane, identified as scapular plane (Reed et al., 2013b, Szucs and Borstad, 2013, Seitz and Uhl, 2012b, Moraes et al., 2008) allows proper balance of force couples and ensure dynamic stabilization of the shoulder throughout the entire range of motion. The directions of force produced by the muscles acting on the humerus and scapula are shown in **Erro! Autoreferência de indicador não válida.**.

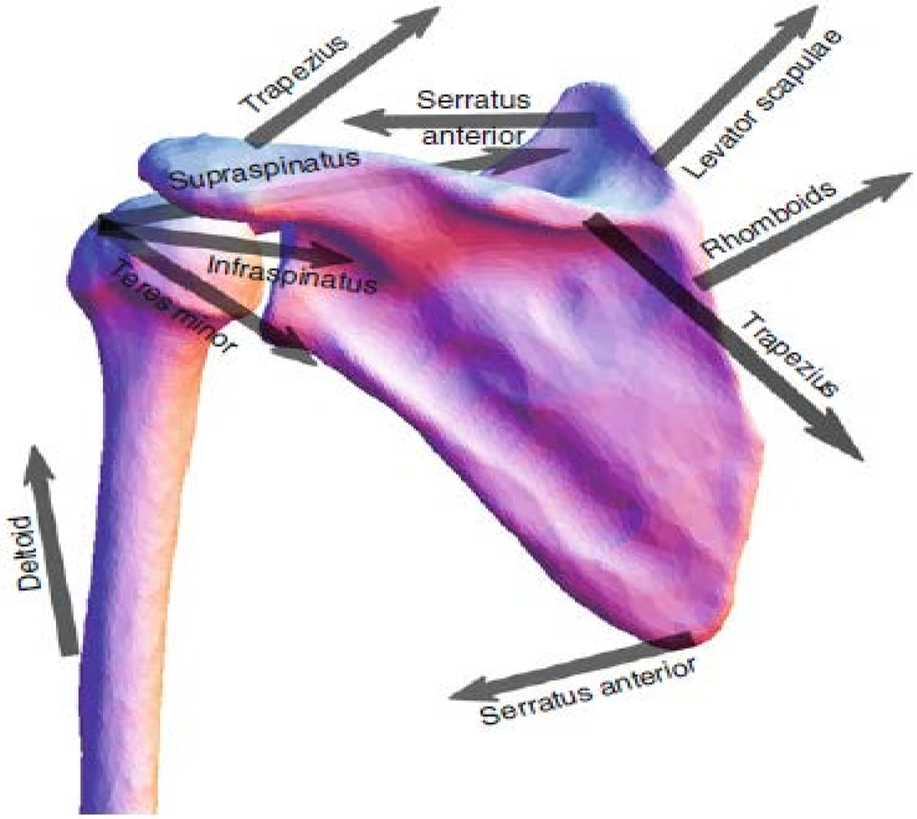


Figure 1. The scapular rotators position the scapula to achieve motions with efficient biomechanics to allow for optimum shoulder function. Source: ahmad et al. (2014), p 27.

For example, the trapezius function, in upward rotation of the scapula, helps optimally position the glenoid fossa during overhead motions (Cael, 2012).

Due to the important role that the shoulder musculature has in producing and controlling shoulder motion, impairments of these muscles could alter the motion of the scapula, clavicle and/or humerus, leading to impingement syndrome, rotator cuff tears and glenohumeral instability (Ebaugh et al., 2006). Altered scapular kinematics has been identified in individuals with impingement syndrome (Ludewig and Cook, 2000a, Lukasiewicz et al., 1999). The synchronous upward rotation of the scapula, as the arm is elevated, is believed to be necessary to maintain an appropriate length tension relationship for the deltoid, with implications in the elevation movements in all planes.

Scapular motion is particularly important during shoulder abduction and flexion. This motion is known as scapulohumeral rhythm. Measurement of this motion shows that the ration of glenohumeral movements to scapulothoracic movement has been traditionally reported as 2:1 during abduction (Ahmad et al., 2014). However Yano et al. (2010), proposed two types of upward rotation at the initial phase of elevation: in the glenohumeral type (much glenohumeral joint motion and less scapular motion), the scapula slightly rotated downward and then progressed upward, and in the scapulothoracic type (much scapular motion and less glenohumeral joint motion), the scapula directly rotated upward. Either way, the ability to control and coordinate the movement of the scapula in relation to the humerus is essential for stability of the glenohumeral joint (Ahmad et al., 2014).

Although there is some evidence on the contribution of the scapular muscles to the development of the condition, evidence focusing on the glenohumeral muscles, which are responsible for the active centering of the humeral head in the glenoid during active movements, is lacking.

There is evidence, from in vivo kinematic studies, that the subacromial space is altered by the effect of muscular activity. A study by Graichen et al. (2005), suggested that the subacromial space can be effectively widened by adducting muscle activity, which effects the position of the humerus relative to the glenoid, reducing the superior migration of the humerus (pathogenesis of the impingement syndrome). This is important because it indicates that alteration of the subacromial space may be caused by downward translation of the humeral head instead of solely alterations of scapular position as previously thought. The study employed open magnetic resonance (MR) imaging and 3D processing technology in vivo. MR imaging can only allow for a quasi-static assessment. The methodology employed by Dal Maso et al. (2015), using markers fitted to pins inserted into the scapula and humerous would enable dynamic assessment of the joint and is a more accurate method of measurement.

Tasaki et al. (2015), also using MR found that even in an asymptomatic health shoulder the rotator cuff came into contact with the acromion and the acromioclavicular joint in six cases out of 20, when the shoulder was elevated in the scapular plane. They have also reported the importance of the rotator cuff role to prevent impingement, since they acted as a depressor for the humeral head.

2.4 SUMMARY OF SHOULDER ANATOMY AND PATHOLOGY

It is acknowledged that static and dynamic factors could both potentially operate in all ranges of motion throughout the shoulder. However, there is agreement within the literature that the static factors are primarily responsible at the end-ranges of the shoulder motion when under tension, and dynamic factors are primarily responsible in the mid-ranges of the shoulder, when the capsule and ligaments are lax.

In terms of functional anatomy, rotator cuff muscles rotate and depress the humeral head during abduction, which is critical for glenohumeral stability. The deltoid is a prime mover for nearly all movements of the shoulder. It is also an important stabilizing structure since it compresses the humerus to the glenoid fossa. When all fibres of the deltoid work together, it is a powerful abductor, while the supraspinatus stabilizes the head of the humerus as the deltoid abducts the shoulder and prevents impingement of the humeral head on the acromion process.

Limited agreement was found in studies on the normal shoulder motor control, during unconstrained movements in the frontal, sagittal and scapular plane elevation. None of the above mentioned studies were comprehensive enough to include all the muscles surrounding the shoulder girdle, with each only looking at few muscles (mostly scapular muscles). A more comprehensive evaluation of the shoulder muscles is needed in order to settle the complete sequencing of muscle contraction on each of the above mentioned elevations.

It is still not clear if the adduction muscle activity causes an increase of scapular tilting and a decrease of the scapula-humeral rhythm, which indirectly causes an enlargement of the subacromial space or that the adduction muscle activity causes a downward translation of the humeral head relative to the humerus and thus also widens the subacromial space width directly.

CHAPTER III: SENSORIMOTOR SYSTEM

3.1. INTRODUCTION

Maintaining functional joint stability through complementary relationships between static and dynamic restraints is the role of the sensorimotor system (Riemann et al., 2002, Riemann and Lephart, 2002a, Riemann and Lephart, 2002b).

The sensorimotor system has been defined, by Lephart et al. (Riemann and Lephart, 2002a, Riemann and Lephart, 2002b, Myers et al., 2006) as all the sensory, motor and central integration and processing components involved in maintaining joint stability, representing both proprioception and neuromuscular control. Proprioception enables the awareness of current and changing positions of the involved joints as far as the precise force required to perform the task (Riemann and Lephart, 2002b). Components of proprioception are joint position sense, threshold to movement detection and sensation of force (Myers et al., 2006). Neuromuscular control is the unconscious motor efferent response to afferent sensory (proprioceptive) information (Myers et al., 1999). Proprioception is a component of neuromuscular control (Myers et al., 1999) and it plays a major role in muscular control, empowering precision of motion and joint stability (Boerboom et al., 2008).

Sensory information (proprioception) travels through afferent pathways to the CNS, where it is integrated with input from other levels of the nervous system, eliciting the efferent motor responses (neuromuscular control) vital to coordinated movement patterns and functional stability (Myers and Lephart, 2000).

3.1.1 PROPRIOCEPTION

There are 3 conscious sub modalities to measure proprioception, joint position sense (JPS), kinesthesia and force reaction (sense of resistance, tension or force). JPS test measures the accuracy of position replication and can be conducted actively or passively in both open and closed kinetic chain, it refers to the ability to consciously recognize where a joint is orientated in space. Kinesthesia measures the threshold to detection of passive motion and targets the slow-adapting mechanoreceptors, such as ruffini endings or Golgi-type organs and describes the ability to appreciate torque generated within a joint. The sense of tension is measured by comparing the ability of participants to replicate torque magnitudes produced by a group of muscles under varying conditions, which represents the ability to produce a predetermined amount of force (Riemann et al., 2002, Herrington et al., 2009, Myers and Lephart, 2000, Dover and Powers, 2003, Dover et al., 2003, Janwantanakul et al., 2001).

The measurement of joint positional sense is commonly assessed by active replication, where the limb is passively moved to a predetermined angle and held for a few seconds. The subject relaxes and returns the limb to the starting position. The subject then attempts to actively reposition the limb to the target angle. The difference between the target angle and the repositioned angle is then calculated (Dover et al., 2003, Dover and Powers, 2003, Herrington et al., 2009, Janwantanakul et al., 2001, Myers et al., 1999, Myers and Lephart, 2000).

Kinesthetic deficits have been measured using threshold to detection of passive motion. This ability to detect movement also appears to be velocity dependent, with detection being more precise at slower speeds (Allegrucci et al., 1995). Kinesthetic awareness testing of the shoulder has been assessed using a proprioception testing device, which consisted of a motor-driven goniometer that passively moved the shoulder at a predetermined speed through an arc of movement. A rotational transducer and a digital microprocessor, which measures angular displacement, was also used (Allegrucci et al., 1995, Safran et al., 2001, Boerboom et al., 2008).

Measurement of the sense of tension or force (force-reaction or force-reproduction, FR), involves the use of a reference force, usually determined as a percentage of maximal voluntary isometric contraction, that the subject has to replicate. This measurement could be of particular interest, since the glenohumeral joint primarily relies on dynamic restraints to maintain stability, so the neuromuscular control of the rotator cuff is important to stabilize the glenohumeral joint and prevent injury. Dover and Powers (2003), explored this further and suggested that participants generated significantly more force in the internal rotation position than in the external rotation position (a position of great importance in overhead sports). This was suggested as being of clinical interest and relevance to clinicians because FR is considered to be a more clinically relevant measure of shoulder proprioception. Force reaction may provide more muscle activity and afferent information than JPS during proprioception measurements. However more studies measuring proprioception in an injured population or during rehabilitation are needed to demonstrate the significance of FR.

Although position sense accuracy have been seen to vary across ROM as stated by Janwantanakul et al. (2001), few of the reviewed studies on active joint position sense explored this phenomenon. Janwantanakul et al. (2001) and Herrington et al. (2009), suggest that position sense acuity seems to be enhanced near the end of rotation range where there is more tension on the restraints to movement.

3.1.2 MOTOR CONTROL

One of the most commonly seen features in human movement is motor variability. Several attempts at the same task always lead to somewhat different patterns of performance, including the kinematics, kinetics, and patterns of muscle activation, where each repetition of an act involved unique, nonrepetitive neural and motor patterns (Latash et al., 2002). In fact, motor variability has become an object of study in its own right, mostly because it informs an understanding of the central organization of the system that produces voluntary movements.

Latash et al. (2002), also proposes that one of the origins of motor variability is motor redundancy, since a motor task does not develops on a single motor pattern and the central nervous system is confronted with a problem of choice.

In terms of motor control, although high variability exists, a trained movement can occur in a feedforward manner, in which the early onset of muscles prior to movement exists in a preprogrammed response of the central nervous system. Learning motor skills evolves from the effortful selection of single movement elements to their combined fast and accurate production (Diedrichsen and Kornysheva, 2015).

3.2 PHYSIOLOGY OF THE SENSORIMOTOR SYSTEM

During an upper limb movement, the corticospinal system generates a motor sequence that activates muscles in coordinated sequences to create joint motion. This motor program must create the optimal conditions of stability at the proximal joint of the upper limb aimed at generating the transferring forces to the distal segments in an efficient manner. If these stable conditions are achieved, the rapid upper limb movement will not disturb body equilibrium during overhead activities (Severini et al., 2014).

In terms of motor control, agonistic and antagonistic muscle groups must have coordinated muscle contractions to maintain a stable shoulder joint during movement (Ahmad et al., 2014). Ordinarily, when an agonist performs a desired motion, the antagonist is inhibited. If both contracts, then co-contraction occurs and it is able to provide stability to the joint. Muscles that help the desired action are called synergists. Synergists may assist the agonist indirectly either by stabilizing a part or by preventing an undesired action (Levangie and Norkin, 2011).

Proprioception testing methods are dependent on conscious appreciation (perception) of mechanoreceptor signals. Proprioceptive information travels to the higher brain centers through the dorsal lateral tracts (conscious appreciation) and the spinocerebellar pathways (stimulation and regulation of motor activities) (Riemann et al., 2002).

The sources of conscious proprioceptive information include joint, muscle, and cutaneous mechanoreceptors, additionally, visual and auditory signals can provide additional cues to joint positional sense and kinesthesia.

Niessen et al. (2009), found significantly larger mean errors during active reproduction of joint position when compared to the passive mode. Moreover, participants were significantly less accurate during the active mode. Nissen concluded that human skeletal muscles possess thixotropy which means it has a history-dependent mechanical property. This means that the degree of passive muscle stiffness and resting tension is dependent on the immediately preceding history of contractions and length changes and this propriety is directly related and affects passive joint position sense.

3.2.1 RECEPTORS INVOLVED IN PROPRIOCEPTION

The perception and execution of musculoskeletal control and movement is mainly mediated by the central nervous system. The somatosensory, the vestibular and the visual systems monitor the perception and sensation of joint movement (Rozzi et al., 2000). Lephart et al. (1994), define proprioception as a specialized variation of the sensory modality of touch but proprioception may be considered the cumulative neural input, integrated in the central nervous system, arising from mechanoreceptors located in the joint capsules, ligaments, muscles, tendons and skin (Carpenter et al., 1998, Myers and Lephart, 2002, Lee et al., 2003).

JOINT MECHANORECEPTORS

There are four types of joint mechanoreceptors which are generally described by the stimulus they respond to and/or by the joint state in which they activate (static and/or dynamic), the intensity of the stimulus need to activate them (low or high-threshold) and their ability to remain active (slowly adapting), or not (rapidly adapting) when the stimulus is constant (Williams et al., 2001).

Rapidly adapting receptors are important to joint movement sense (Lephart et al., 1997, Lephart et al., 1998, Riemann and Lephart, 2002a, Riemann and Lephart, 2002b, Williams et al., 2001). Pacinian corpuscles are fast adapting, low-threshold receptors that respond to vibration, pressure and movement acceleration or deceleration stimulus and can be found in the joint capsule and ligaments, signaling information during dynamic joint activities (Grigg, 1994, Lephart et al., 1997, Williams et al., 2001).

Slowly adapting receptors are important to joint position sense (Lephart et al., 1997, Lephart et al., 1998, Williams et al., 2001, Lee et al., 2003) due to their ability to provide continuous feedback like Ruffini endings, Golgi tendon organ-like receptors and free nerve endings. Ruffini endings can be found in ligaments and joint capsule and are sensitive to joint position, joint motion and intra-articular pressure. They are believed to perform as static and dynamic receptors, having slow-adapting characteristics and low activation thresholds but are excited only during extreme joint rotations (Grigg, 1994, Lephart et al., 1997, Hogervorst and Brand, 1998, Williams et al., 2001). Golgi tendon organ-like endings are high threshold receptors with slow adapting characteristics that are sensitive to tension in ligaments and menisci during dynamic tasks, mainly at end-range of motion (Lephart et al., 1998, Williams et al., 2001). Lastly, free nerve endings can be found largely in the capsule, ligaments, fat pads and menisci and are sensitive to pain arising from mechanical or chemical origin. These receptors become active in the presence of a noxious stimulus responding in static or dynamic tasks, based in their high threshold and slow adapting characteristics (Hogervorst and Brand, 1998, Lephart et al., 1998, Williams et al., 2001).

However, the literature is inconsistent regarding the function of these skin mechanoreceptors. Lephart et al. (1997), suggested that joint mechanoreceptors could provide information as complement to the input of muscle and tendon mechanoreceptors. Williams et al. (2001), however, stated that although joint mechanoreceptors could play a role in joint position sense and kinesthesia, their primary role was signaling the approach of end-range of motion preventing movement beyond the limits of motion, being less relevant to proprioception than muscle and tendon mechanoreceptors.

In the case of the shoulder, these joint mechanoreceptors are located mainly in the inferior glenohumeral ligament (Jerosch et al., 1993) and have stretching ability due to a serpentine configuration. Although this work was undertaken on cadaveric samples, they were aged between 25-59 years old, with a harvest time of 3-12h after death, suggesting that the specimens maintained most of their original characteristics. However, this type of analysis do not allow comparison of mechanoreceptors density across the capsule and ligaments, thus it is not possible to assume that the inferior glenohumeral ligament has more mechanoreceptors, when compared to other ligaments, it emphasized the importance of the inferior capsule-labrum complex for passive stability.

SKIN MECHANORECEPTORS

There are many nerve endings that are found in the skin, however, it is the ones that are expanded and encapsulated that act as mechanoreceptors. Meissner corpuscles are encapsulated dendrites that respond to changes in texture and slow vibrations. Merkel cells are expanded dendritic endings that signal sustained pressure and touch. Ruffini corpuscles are enlarged dendritic endings that respond to sustained pressure and Pacinian corpuscles are encapsulated dendrites that respond to deep pressure and fast vibration. When present, hair follicle receptors may also be relevant (Barret et al., 2009).

Skin mechanoreceptors may play a role regarding joint position and kinesthesia when the skin is stretched (Hulliger et al., 1979, Macefield et al., 1990, Edin and Johansson, 1995). Consequently, cutaneous receptors are activated mostly at extreme range of motion (Burke et al., 1988).

According to Rienmann and Lephart (Riemann and Lephart, 2002a, Riemann and Lephart, 2002b), the relevance of the information provided by cutaneous mechanoreceptors is dependent on their density in a given body area. Cutaneous mechanoreceptors are more relevant in finger movements that in other body parts where their density is lower and not representative of the preferred proprioceptive strategy for shoulder. According to Umeda et al. (2014), discharges of muscle-related receptors reconstructed joint kinematics more accurately than discharges of tactile-related receptors (skin mechanoreceptors). Furthermore, skin mechanoreceptors improved the accuracy of joint kinematic estimation. The limited role of skin mechanoreceptors on the proximal limb joints compared to fingers is further concurred by Collins et al. (2005), mostly because the number of muscle spindles (muscle-related receptors) acting on the proximal joints are larger than on the fingers (Scott and Loeb, 1994).

MUSCLE AND TENDON MECHANORECEPTORS

Muscle and tendon mechanoreceptors are the most significant for proprioception and functional joint stability. Golgi tendon organs and muscle spindles are the most important of this group and according to Shields et al. (2005) the information provided by muscle spindles is pivotal. These mechanoreceptors are a major source of joint kinematic information (Umeda et al., 2014).

Golgi tendon organs (GTO) are slow adapting receptors (Lee et al., 2003) with low threshold (Barret et al., 2009) irregularly spaced along the muscle-tendon complex and are sensitive to variations in muscular tension during contraction or stretching tasks (Sargant, 2000, Guyton and Hall, 2006, Levangie and Norkin, 2011) but are frequently neglected in theories of motor control (Kistemaker et al., 2013). They provide joint position feedback (Myers and Lephart, 2000) and muscle-tendon complex tension (Myers and Lephart, 2000, Riemann and Lephart, 2002a). The feedback provided by these receptors to joint position and movement is important during active tasks but less relevant when the muscles are relaxed (Riemann and Lephart, 2002a, Kistemaker et al., 2013). Kistemaker et al. (2013), argue that the minor relevance of the GTO assumed in literature regarding movement control might be because their function is not fully understood. In fact, literature still debates the characteristics of the feedback provided by GTO, whether it is positive or negative. Guyton and Hall (2006) and. Barret et al. (2009) both suggest that the input provided by GTO to the spinal cord will activate an inhibitory motor neuron, reducing the activity of the muscle being exerted through negative feedback. However, recent research (Van Doornik et al., 2011) has been providing evidence of positive feedback provided by group I afferents.

Muscle spindles (MS) can be found in every skeletal muscle, in varying numbers. These receptors are particularly numerous in neck muscles because head position and movement sense is crucial to control posture and in intrinsic muscles of the hand due to their enrolment in fine manipulations. They are rapidly adapting receptors consisting of intrafusal muscle fibres, arranged in parallel with skeletal muscle fibres and a capsule with two thin contractile extremities and a larger non-contractile middle part, protecting groups of 4-15 intrafusal muscle fibres (Rossi-Durand, 2006). The innervation of contractile elements of intrafusal fibres (gamma-motor neurons) is independent of that of extrafusal (alpha-motor neurons), skeletal muscle fibres (Riemann and Lephart, 2002a, Guyton and Hall, 2006, Barret et al., 2009). These spindle fibres are sensitive to the length and the velocity of lengthening of the extrafusal muscle fibres. Sending messages to the cerebellum about the state of stretch of the muscle (Levangie and Norkin, 2011).

Both the Golgi tendon organs and the muscle spindles provide constant feedback to the central nervous system during movement in order that appropriate adjustments can be made, and they also help to protect the muscle from injury by monitoring changes in muscle length (Levangie and Norkin, 2011).

Primary and secondary sensory endings are associated with intrafusal muscle fibres (Rossi-Durand, 2006) and are sensible to changes in muscle length and respond during all range of motion (Grigg, 1994, Myers and Lephart, 2000, Riemann and Lephart, 2002a). Stretching the whole muscle or contracting the extremities of the intrafusal muscle fibres (even if the length of the muscle doesn't change) will cause both sensory endings to send input to the central nervous system, generating a reflex response of the muscle's motor neurons, producing a reflex contraction of the large skeletal fibres of that muscle and near synergists (Guyton and Hall, 2006, Rossi-Durand, 2006). The activation of the gamma-motor neurons allow the modulation of muscle spindles sensitivity (Lephart et al., 1997, Needle et al., 2013) when the extrafusal muscle fibres are shortened, allowing spindles to be functional during the whole length of a muscle contraction. If a muscle is loaded further than the anticipated level the shortening of the intrafusal fibre will surpass the extrafusal shortening and stretching the MS in the central region will cause a burst in excitatory potential from spindle afferents (Lephart et al., 1997).

Needle et al. (2013) observed an increase in the activity of muscle spindles afferents during joint loading of individuals with unstable ankles and healthy ankles, supporting the compensatory role of these receptors for joint proprioception and kinesthesia, which may explain why mechanical joint laxity is not always synonymous of decreased joint sensation (Hubbard et al., 2007) or why a joint sprain does not always develop joint sensation deficits or functional instability (Eastlack et al., 1999). They suggest that joint instability may be the result of a fusimotor system dysfunction and not the result of mechanical laxity. However, this has yet to be explored in the shoulder.

In summary, several sources of proprioceptive input can be identified. Afferent input from muscle, tendon, joint and skin receptors are integrated, together with information provided by the central nervous system, in the muscle spindles. All information provided to the muscle spindles is adjusted to generate a single signal to be transmitted to the central nervous system and then to the alpha-motor neuron to modulate the muscle's activity. All the referred receptors act as complementary sources of information regarding joint and movement sensation (Kistemaker et al., 2013).

3.3 FACTORS THAT INFLUENCE THE SENSORIMOTOR SYSTEM

It has been suggested earlier that muscle control may be affected by pain (Hodges and Moseley, 2003, Hess et al., 2005, MacDonald et al., 2009). Hess et al. (2005), propose that the subscapularis onset, in a task of rapid external rotation movements, tends to be significantly delayed under the presence of pain. Electrostimulation also seems to impair motor control (Monjo and Forestier, 2015), however further studies are needed to confirm these findings. In their study, Monjo and Forestier (2015), have used electrostimulation to generate electrically-evoked contractions that led to neuromuscular fatigue and consequently adaptive neuromuscular strategies aiming to maintain the initial postural control. Their reliability study only explored differences between trials.

Proprioception has been described as a modus to prevent injury, avoiding non-physiologic joint movements, as well as contributing to the coordination of complex movement systems (Jerosch and Prymka, 1996). However, when injury occurs, the result may be mechanical instability and alteration to the sensorimotor system leading to functional instability. It is suggested that this might constitute a mechanism of re-injury. The sensorimotor alteration occurs because many of the mechanical restraints of the joint are mechanoreceptors that contribute to proprioceptive information (Myers et al., 2006).

Munn et al. (2010), undertook a systematic review of the literature and meta-analysis to explore sensorimotor deficits that exist within functional ankle instability (pathological condition). They suggest that participants with unstable ankles, when compared to healthy controls, had sensorimotor impairments in passive joint position sense, active joint position sense, postural sway in single-leg stance, the star excursion balance test and time to stabilization from a single-leg jump in a medio-lateral and an antero-posterior direction.

The influence of sports practice on the sensorimotor system has been a matter of great discussion and criticism in the literature, and mostly in relation to whether sports practice has a beneficial/maleficial impact on the proprioceptive mechanism. Exercise has been described as having the potential for disrupting proprioception mostly because of the fatigue and its effect on awareness of joint position, movement and sensation of force (Proske and Gandevia, 2012). Since mechanoreceptors are present in the musculature surrounding the joint, it is hypothesized that as muscle fatigues, proprioceptive feedback is affected, and thereby, neuromuscular control and shoulder function are affected (Myers et al., 1999, Myers and Lephart, 2000).

Studies on normal participants to explore differences between pre- and post- fatigue protocols, suggested that shoulder proprioception in active repositioning, in shoulder external rotation, is significantly altered when the muscle mechanoreceptors are dysfunctional due to muscle fatigue (Lee et al., 2003, Myers et al., 1999, Voight et al., 1996). Carpenter et al. (1998), found that threshold to detection of passive motion or kinesthesia was also altered after applying a fatigue protocol. However, Sterner et al. (1998) did not find differences in either active reproduction of passive positioning or active reproduction of active positioning before and after adopting the fatigue protocol. It could be suggested therefore that the differences may be related to the differences identified in the fatigue protocol, however, as may be seen, the fatigue protocols were similar: Lee et al. (2003), described their fatigue protocol with a warm up of 10 min (push-up exercises) and isokinetic arm rotations with maximal effort until decrease in 50% of the maximum voluntary contraction. The Voight' protocol (Voight et al., 1996) of fatigue included continuous concentric internal and external rotation exercises of the shoulder until 3 consecutive repetitions achieved less than 50% of the subject's maximum peak torque for external rotation. Myers et al. (1999), used the same protocol as Voight. Sterner et al. (1998), warmed up the participants with 15 submaximal concentric contractions on the isokinetic dynamometer followed by five maximal reciprocal concentric contractions for the shoulder external and internal rotation for the establishment of the maximum voluntary contraction (MVC). The fatigue protocol consisted of continuous maximal reciprocal concentric contractions until external rotation peak torque decreased below 50% of the MVC. Carpenter' protocol (Carpenter et al., 1998) included internal and external rotation using an isokinetic dynamometer. The fatigue criteria demonstrated decreased MVC of the internal rotators peak torque by

50%. Thus, the difference between the work of Sterner and the other studies may lie in the choice of angles, since Sterner were the only one who measured midrange angles.

Conversely, it is also reported that regular physical activity causes muscular and neural adaptations that may have a positive effect on proprioception such as reflex motor unit facilitation of contraction and increased motor unit synchronization (Thompson et al., 2003, Duchateau et al., 2006). Aagaard et al. (2002), advocate that resistance training leads to neural adaptations at supraspinal and spinal levels such as increased neural drive in descending pathways, increasing motoneuron excitability.

Xu et al. (2004), demonstrated that elderly practicing Tai Chi had better kinesthesia in the knee and ankle than those practicing swimming, running or not practicing physical activity. However, these results should be interpreted with caution since participants were neither blindfolded nor provided with headsets to avoid visual and auditory clues (Allegrucci et al., 1995). In addition, they did not perform any mental evaluation for cognitive impairment. More recent work by Liu et al. (2012), in which 60 elderly participants randomly allocated in three groups (Tai Chi, proprioception exercise and no structured exercise) experienced a 16 consecutive weeks protocol, which concurs with the work of Xu et al. (2004). Tai Chi and proprioception exercise groups demonstrated significantly better joint position sense than the control group. An earlier study by Thompson et al. (2003), further supports these findings, although they did not screened their participants for potential cognitive impairment. However, the evidence proposed does strengthen the results evidencing the positive effects of a resistance training program in knee active joint position sense and kinesthesia.

Regular physical activity does not modify the number of mechanoreceptors (Ashton-Miller et al., 2001) but, according to Hutton and Atwater (1992), induce morphologic adaptations in muscle spindles. At the central level, regular physical activity modulates the muscle spindle gain and induces plastic changes in the central nervous system. Increased muscle spindle output increases the strength of synaptic connections and/or and induces structural changes in the organization and number of connections among neurons. These plastic adjustments in the cortex could modify the cortical maps, increasing the cortical representation of joints and, consequently, increasing proprioception (Ashton-Miller et al., 2001).

In summary the studies discussed in this chapter produce evidence of the positive effect that physical activity can have on the proprioceptive system, but acknowledges that fatigue may decrease it. However, evidence exploring the effect of physical activity in shoulder proprioception is less convincing, and will be further discussed on the next section.

3.3.1 SHOULDER ADAPTATIONS TO THE OVERHEAD SPORTS PRACTICE AND INFLUENCE ON THE SHOULDER SENSORIMOTOR SYSTEM

Myers and Lephart (2000), undertook a seminal review of the proprioceptive mechanisms in the athletic shoulder. These findings indicate that in throwing athletes the presence of significant capsular laxity and excessive range of motion lead to diminished proprioception, because after capsuloligamentous injury decreases the proprioceptive input which in turn decreases neuromuscular control, thereby leading to instability. Whilst the review was comprehensive, their search strategy was omitted. An early study by Allegrucci et al. (1995), using the threshold to detection of passive motion found that healthy upper extremity athletes may have kinesthetic deficits in their throwing shoulder, compared to their non-dominant shoulder. Their study focused in several overhead sports, with their preference lying through the unilateral.

Literature exploring joint positional sense, includes work by Dover et al. (2003), who compared softball and soccer players (tracked athletes as controls) and measured active joint position sense. Softball athletes produced significantly greater external rotation error scores than non-throwing control athletes, but not for internal rotation, flexion and extension error scores. Conversely, Boyar et al. (2007), proposed that male adolescent tennis players were more accurate than age-matched sedentary controls regarding passive joint position sense. However this phenomenon was not side specific, thereby suggesting that there is no real adaptation in overhead sports training. The differences reported may be due to the effect of passive repositioning, which is considered to be less challenging to proprioceptors. Moreover, Boyar et al. (2007) studied middle range angles of 15º and 30º and avoided end of range, which may also contribute to the different findings. So, although both studies evaluated joint positional sense, they also differed in modalities (the first active and the second passive), target angles and use of evaluation instruments. Boyar et al. (2007), used an isokinetic dynamometer and Dover et al. (2003), used an inclinometer. The study by Dover et al. (2003) supported the idea that throwing athletes have decreased proprioceptive acuity when compared to non-throwing athletes. The changes in capsular and muscular structures around the shoulder may lead to mechanoreceptor malfunctioning resulting in partial deafferentation and decreased proprioceptive acuity (Voight et al., 1996). However, recent research on volleyball (Nodehi-Moghadam et al., 2013) proposed that throwers experience some adaptive changes over time, mostly because of the repetitive movements of throwing, which can lead to improved proprioceptive abilities. The study compared female volleyball players and healthy volunteers exploring passive joint position sense and kinesthesia. Findings indicated that volleyball players had significantly lower error scores than the control group. Although they have rotated passively the shoulder at 1deg/s, a value that does not represent the natural acceleration of the arm during playing volleyball, with the reported angular velocity of approximately 4520º/sec for shoulder internal rotation (Wagner et al., 2014), this is relevant because they had got a training effect improving sensorimotor accuracy, and it is suggested that it related to the repetitive nature of the performed gestures. Nevertheless, no difference was found for kinesthesia.

One of the most complex motions of the upper body, is the throwing movement, which requires coordinated powerful muscle contractions along with deep stabilization of the glenohumeral joint (performed by the rotator cuff). This action involves pectoralis major, latissimus dorsi, anterior deltoid and triceps to pull the arm forward and across the body. Once the ball is released, the posterior deltoid, teres minor, infraspinatus, rhomboids, and trapezius must eccentrically contract to slow the motion of the arm (Cael, 2012).

Electromyography analysis of the throwing arm has shown deceleration to be the most vigorous phase of rotator cuff muscle activation (Moynes et al., 1986, Jobe et al., 1983). During the late phase, however, some differences have been noted between the muscle activity of the professional and amateur athletes. Professional athletes had moderate to minimal supraspinatus muscle activity, and the amateurs had marked to moderately strong muscle activity (Moynes et al., 1986). However, whilst this reference is now quite dated there is no more up to date literature on which to draw.

Earlier studies by Jobe et al. (1984), reported the similarity of the biceps and brachialis firing patterns and suggest that the biceps functioned predominantly as an elbow muscle rather than at the shoulder during follow-through phase on baseball. Therefore, it could be hypothesized that in overhead sports other than baseball, where there is greater elevation of the glenohumeral joint, such as volleyball, that the biceps contribution to the shoulder stability should be greater. This was similarly proposed for triceps muscle, theorizing that triceps role on shoulder stability would be greater on overhead sports that rely on higher degree of shoulder flexion and abduction like volleyball. During the same phase, the pectoralis major and latissimus dorsi, as internal rotators, assist the subscapularis in carrying the arm across the chest. Controversially, this would suggest more emphasis on concentrically activation of internal rotators rather than eccentric control from the external rotators (Byram et al., 2010). In this publication, which looked at preseason shoulder strength measurements in professional baseball pitchers, were studied in an attempt to identify players at risk for injury.

More recent work by Escamilla and Andrews (2009), has contributed to the literature by suggesting that scapular muscles action is important as they enable optimal position of scapula in relation to the humerus and prevent shoulder injuries, mostly when motion occurs overhead, with an extremely rapid movement. It is hypothesized that high shoulder forces and torques are generated, especially during the volleyball spike.

3.4 SUMMARY OF SENSORIMOTOR SYSTEM THEORY

The anatomical configuration of the glenohumeral joint affords great mobility to the joint but to the detriment of stability. The lack of osseous stability requires the shoulder to rely on an interaction between static and dynamic structures to provide joint stability and it is mediated by the sensorimotor system (Myers and Lephart, 2000). Several types of proprioceptive testing have been described, namely joint position sense, sensation of force or force reaction and kinesthesia.

According to Myers et al (Myers et al., 1999) the articular mechanoreceptors are best stimulated at end range of motion, whereas muscle spindles, due to their gamma motor-neuron innervation, allow for readjustment of muscle tension and joint position sense at all times during activity.

An overarching criticism of studies reviewed was that none were blinded either for study participants and investigators and most of them did not report any reliability studies of their data collection methods. The participants were not representative of the population from which they were recruited. Little to no information regarding force reaction and active position sense of the shoulder was found, focusing mainly on the differences between internal and external rotation and mid to end of range characteristics. Although there is some consensus on the deleterious effect of overhead sports on shoulder proprioception, there is no absolute agreement on the literature and more work is needed.

In the field of motor control, studies were found which investigated shoulder muscles onset, however, none of the studies involved volleyball players. This lack of research would indicate that more studies are needed to establish the sequence of muscle firing in volleyball players. The lack of evidence from the literature would support the need for further investigation into measurement and action of shoulder muscles in both the normal and sports practitioners.

CHAPTER IV: SHOULDER IMPINGEMENT SYNDROME

4.1 INTRODUCTION

Since 1983 the high prevalence of shoulder complaints, consistent with shoulder impingement syndrome (SIS), have been reported (Neer, 1983). SIS has traditionally been defined as compression and mechanical abrasion of the rotator cuff structures as they pass beneath the coracoacromial arch (the subacromial space) during elevation of the arm (Neer, 1983). It has also been described as inadequate space for clearance of the rotator cuff tendons as the arm is elevated (Ludewig and Cook, 2000a). This syndrome is the most common disorder of the shoulder, resulting in functional loss and disability in the patients that it affects (Michener et al., 2003).

As detailed in chapter two, the subacromial space is defined by the humeral head inferiorly, the anterior edge and inferior surface of the anterior third of the acromion, coracoacromial ligament and the acromioclavicular joint superiorly (Neer, 1972). The tissues that occupy the subacromial space are the supraspinatus tendon, subacromial bursa, long head of the biceps brachii tendon, and the capsule of the shoulder joint (Michener et al., 2003). Any or all of these structures may be affected by SIS, because SIS refers to collision between the rotator cuff (the supraspinatus, infraspinatus, teres minor and subscapularis tendons) and the acromion and coracoacromial ligament (Bandholm et al., 2006). The location of supraspinatus tendon is underneath the acromion, which makes this muscle particularly vulnerable to tendinosis, impingement and tearing. The subscapularis tendon is also particularly vulnerable to impingement during overhead movements (Cael, 2012) and these are particularly painful conditions during abduction and internal rotation of the glenohumeral joint.

However this syndrome has historically been described as a compression of the rotator cuff tendons beneath the acromion. Recent evidence suggests that ‘‘impingement syndrome’’ is not likely to be an isolated condition that can be easily diagnosed with clinical tests or most successfully treated surgically. Rather, it is likely to compose of a complex set of conditions involving a combination of intrinsic and extrinsic factors (Braman et al., 2014a).

The long term, subacromial impingement can result in various stages of rotator cuff disease which range from mild tendon irritation to complete tendon tear (Severini et al., 2014). Nevertheless, a mechanical impingement phenomenon, as an etiologic mechanism of rotator cuff disease, may be distinct from the broad diagnostic label of ‘‘impingement syndrome’’. The concepts of mechanical impingement and movement-related impairments may better suit the diagnostic and interventional continuum, as they support the existence of potentially modifiable impairments within the conservative treatment paradigm (Braman et al., 2014a). Therefore, as advocated by Braman et al. (2014a), the clinical diagnosis of ‘‘impingement syndrome’’ should be eliminated.

4.2 TYPES OF SIS

There are two types of impingement: subacromial (external) and internal. The subacromial concerns the soft tissue encroachment into the subacromial space and the internal impingement involves the encroachment of the rotator cuff tendons between the humeral head and the glenoid rim. Impingement occurs mostly due to repetitive overhead positioning of the arms in sports or in work related activities. Impingement syndrome is identified when at 90º of abduction and 90º of external rotation it is referred posterior shoulder pain (Ellenbecker and Cools, 2010, Cools et al., 2008). Since classification based on the site of encroachment is not enough, it is important to understand whether the problem is primary or secondary. In fact, shoulder impingement etiology is multifactorial and underlying causes can be subdivided into structural and functional mechanisms, often referred to as primary and secondary, also termed as functional impingement (Severini et al., 2014).

PRIMARY IMPINGEMENT

Primary impingement is normally caused by direct compression, and identified by anteroposterior x-rays. It is commonly due to a decrease in the physiological space between the inferior acromion and the superior surface of the rotator cuff tendons (7-13mm in participants with shoulder pain and 6-14mm in normal). The rotator cuff pathology is a result of compressive disease due to mechanical loading (Ellenbecker and Cools, 2010) and occurs because of a narrowing of the subacromial space (Cools et al., 2008).

SECONDARY IMPINGEMENT

In secondary impingement there are no structural obstructions, only dysfunction of the rotator cuff. The function of the rotator cuff is, amongst others, to perform a caudal glide of the humeral head during elevation in order to avoid impingement. When there is greater cranial migration of the humeral head, secondary impingement can result (Cools et al., 2008).

4.3 DIAGNOSIS OF SIS

Cools et al. (2008), have developed a body of work in the study of shoulder pathology and the clinical reasoning underpinning the diagnosis of the condition and rationale for its treatment. They described an algorithm to aid screening of impingement symptoms and sub classification according to signs and symptoms in athletes. A limitation of the algorithm is that it was developed for athletes with sports conditions. However, it is useful for the general population as well, since the cluster of symptoms related to shoulder impingement is not exclusive to athletes. The algorithm involves a series of tests including: impingement tests, instability/provocation tests or apprehension/relocation tests, scapular dyskinesia tests and rotator cuff tests. If a tear is suspected, strength test and specific tear tests are also included. If there are also suspicions of ligamentous laxity then laxity tests are included. When there is biceps pain then the bicipital test is also administered. Although strictly using clinical outcomes, with limited reliability (Burns et al., 2015, May et al., 2010), it is still considered to be a useful tool for both physicians and physiotherapists, mostly because it identifies subgroups with similar clinical characteristics, instead of focusing in one diagnostic test, with reported poor validity and reliability (May et al., 2010).

Diagnosis of SIS is based on at least 3 of the following symptoms: a positive Neer impingement test, a positive Hawkins impingement test, a positive painful arc sign (60–120° of elevation), pain with palpation of the rotator-cuff tendons, pain with isometric resisted abduction, and pain at the shoulder region (Aytar et al., 2015).

However the diagnostic criteria for SIS were mainly based on the presence of a positive impingement test, several clinical studies have suggested that there is an association between SIS and a variety of underlying mechanisms, namely scapular dyskinesia (Burkhart et al., 2003a, Kibler et al., 2013, Kibler et al., 2006, Kibler et al., 2012). Hence, sub classifying SIS patients depending on its underlying mechanism, such as that presented by Cools et al. (2008), would enable further comparisons.

4.4 WHAT CAUSES SIS

Ludewig and Cook (2000a), suggest that there are multiple causes of SIS. These include: anatomical abnormalities of the coracoacromial arch or humeral head; "tension overload," ischemia, degeneration or even inflammation of the rotator cuff tendons and bursa; weak or dysfunctional rotator cuff musculature; weak or dysfunctional scapular musculature, posterior glenohumeral capsule tightness; postural dysfunctions of the spinal column and scapula; bony or soft tissue abnormalities of the borders of the subacromial outlet and finally, shoulder kinematic abnormalities, also referred as scapular dyskinesia (Burkhart et al., 2003a). Nevertheless, in the case of contractile dysfunction of the rotator cuff tendons, it is mostly associated with alteration of the collagen structure, rather than inflammation, so the term tendinosis, not tendinitis, is more appropriate (Littlewood and May, 2007, Littlewood, 2012).

However, as previously described, causative factors depend on whether it is a primary problem (anatomical abnormalities, eccentric overload, intrinsic tendon degeneration through ischemia or aging) (Braman et al., 2014b), or secondary, which are mainly due to instability of the glenohumeral joint, with decrease in the static stabilizers (capsule, ligaments and labrum). Thus excessive overhead and throwing activity that leads to instability, results in increased humeral head translation and consequently alterations in biceps tendon and rotator cuff structures. Such causative factors have been linked to (1) fatigue, which decreases the effectiveness of the dynamic stabilizers (rotator cuff), (2) intrinsic overload and (3) scapular dysfunction that lead to tendon injury (tear), instability and impingement (Ellenbecker and Cools, 2010).

Furthermore, the position of the humeral head in relation to the glenoid cavity is significantly affected by both arm elevation angle and fatigue (Chopp et al., 2010). This in turn has led to the speculation that shoulder injuries are becoming more frequent and severe for people who perform repeated overhead actions (Sood et al., 2007) and upper limb overhead sports practitioners and that after joint injury or fatigue, proprioceptive deficits have been found, and neuromuscular control has been altered (Myers and Lephart, 2000, Myers et al., 1999, Herrington et al., 2009, Roy et al., 2008, Kamkar et al., 1993).

However, irrespective of the causes, inflammation in the suprahumeral space, inhibition of the rotator cuff muscles, damage to the rotator cuff tendons, and altered kinematics are believed to exacerbate the condition (Ludewig and Cook, 2000a). It is this motion of elevation of the shoulder that brings the greater tuberosity in closer contact with the coracoacromial arch, which causes the damage (Flatow et al., 1994). Similarly, frequent or sustained shoulder elevation at or above 60 degrees in any plane, during occupational tasks, has been identified as a risk factor for the development of shoulder pathological conditions (Bjelle et al., 1981, Hagberg and Wegman, 1987). Moreover, besides the peripherally driven nociceptive mechanisms, central sensitization can contribute to the presence of pain in these patients (Littlewood et al., 2013a), where nociceptor inputs can trigger a prolonged, but reversible increase in the excitability of neurons in central nociceptive pathways (Woolf, 2011).

OVERHEAD SPORTS AND SIS

Overhead activities, requiring repetitive arm elevation movements and high velocity actions have been identified as a risk factor for shoulder impingement (Haik et al., 2013, Neer, 1972).

The overhead sports player is susceptible to shoulder pain and, more specifically, shoulder impingement syndrome due to repetitive micro traumatic stresses placed on the athletes shoulder joint complex during the throwing motion, which challenge the surrounding tissues (Nodehi-Moghadam et al., 2013). This is associated with adaptive altered position of the scapula and humerus in the dominant throwing shoulder, which usually is related to muscular activation alterations (Burkhart et al., 2003a), shoulder muscles imbalances (Byram et al., 2010) and shoulder altered kinematics (Burkhart et al., 2003b).

Injury to a professional athlete can result in loss of income and decreased career length and overhead athletes are particularly susceptible to injuries due to the repetitive, demanding nature of the overhead throwing motion. Injuries to the shoulder of these athletes are common, as large amounts of energy are transferred from the lower extremities and trunk to the upper extremity during the throwing motion (Byram et al., 2010).

The overhead athlete with a painful shoulder may have many causative factors, contributing to the symptoms. The term “disabled throwing shoulder” is a general term that describes the limitations of function that exist in symptomatic overhead athletes, in that they cannot optimally perform the task of throwing or hitting the ball (Kibler et al., 2014).

Mihata et al. (2010), observed that the increased horizontal abduction with maximum external rotation, as occurs during the late cocking phase of throwing motion, can be critical for internal shoulder impingement. In their study, using cadaveric models, horizontal abduction beyond the coronal plane increased the amount of overlap and contact pressure between the supraspinatus and infraspinatus tendons and the glenoid. Although only supraspinatus and infraspinatus sites of encroachment were investigated, these findings provide some information on the biomechanics of the impingement process, further work, on non-cadaveric populations is needed in order to establish causative effects. It should however be noted that the study was performed using frozen cadavers, that were left at room temperature prior to anatomical investigation. Moisture loss and stiffness may be artifacts in the results. Further limitation of the study is that cadavers provides limited information of glenohumeral translation, mostly because it is sensitive to muscular activity pattern (Graichen et al., 2005).

Several studies have demonstrated muscle strength imbalances in overhead sports practitioners who developed shoulder pathology (Kibler et al., 2006, Cools et al., 2005, Cools et al., 2004). Imbalance of the eccentrically-activated external rotator cuff muscles versus the concentrically-activated internal rotator cuff muscles is a primary risk factor for glenohumeral joint injuries in overhead activity athletes (Byram et al., 2010).

Weakness and alterations in activation sequencing of the serratus anterior and lower trapezius are frequently seen in the disabled throwing shoulder and these alterations contribute to scapular dyskinesia, which has been associated with impingement and rotator cuff injury (Kibler et al., 2014).

Normally, the scapula efficiently transfers the kinetic energy from the torso to the upper limb, providing a stable base of support so that the upper limb can be correctly positioned in space during the performance of overhead skills. The glenohumeral joint, which is capable of exceptional range of motion is, as previously stated, inherently anatomically unstable and the dynamic stabilizers of the scapula and the humeral head are critical to maintaining the functional integrity of the glenohumeral joint, and to the ability to successfully serve and spike a volleyball (Reeser et al., 2006). However, improper movement of the scapula causes misalignment of the humeral head (Ahmad et al., 2014), caused by altered muscle activation that produce altered kinematics and it has been associated with impingement development and rotator cuff lesions (Burkhart et al., 2003a)

Eccentric loads have also been considered to have damaging effects during a volleyball match (overhead sport) in the acceleration phase of throwing. Humeral internal rotation velocities will reach over 6000 deg/sec, which must be controlled by shoulder external rotators and scapular retractors (Burkhart et al., 2003a). However, high eccentric load that is placed on the external rotators during the deceleration phase of throwing can also lead to intramuscular connective tissue tearing, chronic inflammation and these may lead to muscle weakness (Burkhart et al., 2003a, Levine et al., 2006).

According to Reeser et al. (2010),when compared to baseball, volleyball athletes present reduced load at the elbow, what could explain the relatively low risk of volleyball-related elbow injuries, but an increased range of motion for shoulder frontal and horizontal abduction, representing an increased risk factor for subacromial impingement in these athletes.

4.5 WHAT IS KNOWN AND NOT KNOWN ABOUT PROPRIOCEPTION AND MOTOR CONTROL IN SIS

All the aspects listed above have been described as causative or etiological factors for the development of the condition however, a narrative review of studies assessing scapular kinematics (Ludewig and Reynolds, 2009), noted some consensus among adaptations found in individuals with impingement or rotator cuff diseases. Their study listed the factors as compensatory adaptations to the condition, instead of causative. There is thought evidence of scapular kinematic alterations and altered muscle activation, as previously described on the work of Kamkar et al. (1993), Ludewig and Cook (2000a) or Bandholm et al. (2006). Additionally, and according to Ludewig and Reynolds (2009), scapular kinematic alterations presented by SIS patients also include short rest length of the pectoralis minor, tight soft-tissue structures in the posterior shoulder region and excessive thoracic kyphosis or flexed thoracic postures. However, without longitudinal or experimentally controlled studies, it cannot be determined if identified movement abnormalities are causative, contributory, or compensatory.

Wassinger et al. (2013), explored acute experimental shoulder pain and verified it elicited an increase in scapular upward rotation during humeral elevation. This adaptation may provide protective compensation to subacromial structures during humeral elevation. However, induction of acute organic pain may differ from real situations. This study suggests that the compensatory adaptations exist because of the pain, instead of the idea that the altered kinematics might be the cause of pain, as previously discussed.

Early studies have shown that altered scapular kinematics, such as decreased posterior scapular tilt and decreased upward scapular rotation, occur during shoulder abduction in participants with SIS (Endo et al., 2001, Lukasiewicz et al., 1999). The hypothesized kinematic alterations in scapular motion, presented by SIS patients, have been linked to decreases in serratus anterior muscle activity, increases in upper and lower trapezius muscle activity (Kamkar et al., 1993, Ludewig and Cook, 2000a), or an imbalance of forces between the upper and lower parts of the trapezius muscle (Kamkar et al., 1993, Wadsworth and Bullock-Saxton, 1997). Lower activity of infraspinatus, subscapularis and middle deltoid during arm elevation has also been referred (Reddy et al., 2000).

Ludewig and Cook (2000), found that overhead upper limb work, in construction workers, can result in impingement syndrome. They suggested that when compared to participants without impingement, there was decreased scapular upward rotation at the end of the 31-60º phase of the abduction in the scapular plane movement, increased anterior tipping at the end of the last phase of the movement, and increased scapular medial rotation under the load conditions. At the same time, upper and lower trapezius muscle electromyographic activity increased significantly in the group with impingement, in both the 61-90º and 91-120º phases. However, the upper trapezius muscle changes were apparent only during the 4.6kg load condition. The serratus anterior muscle did not show significant statistical differences. It should though, be noted that the majority of the published work use a healthy group as a comparison, which requires careful interpretation. Results from participants without impingement syndrome might be influenced by the fact that the various provocative impingement tests might be negative if the patient has postero-superior glenoid impingement (Cools et al., 2008). If it was the case, then the amount of the described differences between healthy and unhealthy participants would be decreased.

It is noteworthy that all the identified studies show consensus on the importance of scapular dyskinesia in the development of SIS, or as a consequence of it. Despite the evidence relating to scapular muscle dysfunction, nothing has been published on the contribution of the shoulder muscles to the condition.

Bandholm et al. (2006), suggested that people with SIS also demonstrated greater latissimus dorsi activity during concentric contractions in the range from 40 to 55 degrees of abduction, when compared to controls. Moreover, this was the only study reporting increase in latissimus dorsi activity and needs confirmation by further studies.

A pathological condition such as SIS, also exhibits a difference in the timing of muscle activation. Recent work by Worsley et al. (2013), explored elevation in the sagittal plane, showed significant delayed onset only in serratus anterior muscle (Worsley et al., 2013). Nevertheless, as this was the only study undertaken in the sagittal plane, the evidence should be treated with caution.

Similarly there has only been one study undertaken in the frontal plane, in which timing of muscle activation, during the abduction movement, was delayed in both serratus anterior and lower trapezius (Worsley et al., 2013).

A systematic review (Chester et al., 2010), based on observational studies were conducted to study the impact of shoulder impingement syndrome on muscle activity patterns of the shoulder complex in the scapular plane. However they did not report the coefficient of agreement between the two investigators who performed the identification of the included studies, they also did not use a validated tool to assess its methodological quality. Moreover, conflicting evidence to support their conclusions was reported, arising from the large amount of heterogeneity between the studies, including methods of assessment, the evaluated tasks and the choice of muscles. They suggest that finding from only two studies indicated that there was a delayed activation of lower trapezius in patients with SIS. However they have presented some evidence on the delayed activation of lower trapezius in patients with SIS. These differences need to be investigated in larger, high quality studies and the effects of therapeutically targeting these muscles in a randomized controlled trial. Roy et al (2008), was not included in the review, but recorded the muscular activity of the upper, middle and lower trapezius, serratus anterior, infraspinatus, and anterior and middle deltoid. They also found that the only intergroup difference observed was a delayed recruitment of the lower trapezius which was concurred by Worsley et al. (2013).

There were also no differences found in neuromuscular activity of upper trapezius and serratus anterior between participants with SIS and normal participants (Larsen et al., 2013, Moraes et al., 2008), as would be expected. Moreover, Moraes et al. (2008), described the scapulothoracic recruitment timing, which starts with the contraction of the upper trapezius, followed by the serratus anterior and finished by the middle trapezius and lower trapezius in both SIS and controls. Whilst no differences were found, it should be noted that subgrouping for SIS patients was not performed, nor further evaluation undertaken besides the orthopedic surgeon referral. Moreover only participants with light to moderate impingement were included. Several clinical studies have suggested that there is an association between SIS and a variety of underlying mechanisms, namely scapular dyskinesia (Burkhart et al., 2003a, Kibler et al., 2013, Kibler et al., 2006, Kibler et al., 2012), Thus sub classifying SIS patients depending on its underlying mechanism, such as that presented by Cools et al. (2008), would be a more valuable way to enable comparison. Since the topic remains controversial, more studies on the differences on timing of muscle onset between patients with SIS and controls are needed.

In the same study, there was no difference in muscle recruitment pattern. Moraes et al. (2008), studied side to side differences in scapular muscle latencies and found that the affected shoulder presented greater latency when compared to the non-affected side, but only for the serratus anterior ($p<.001$). These findings indicated that participants with light to moderate impingement syndrome showed late recruitment of the scapular muscles during arm elevation. However, muscular performance of the shoulder rotator muscles was not affected. These results might be carefully analyzed in light of Diederichsen et al. (2009) findings, which suggested an altered shoulder muscle activity pattern on both the symptomatic and asymptomatic side in patients. Further this might be indicative of different motor patterns which may be a pathogenic factor of SIS, perhaps due to inappropriate neuromuscular strategies affecting both shoulders. Diederichsen et al. (2009), found a significant higher upper trapezius muscle activity on the asymptomatic side of SIS patient’s vs healthy controls. Moreover, the work of Lukasiewicz et al. (1999) and Hebert et al. (2002) demonstrated altered kinematics in both the symptomatic and asymptomatic shoulder in SIS patients.

An explanation of the altered motor control, could be that the normal external rotation of the scapula during scaption (shoulder abduction in the plane of the scapula), requires the coordinated action of all parts of trapezius and the serratus anterior. Altered synchronization of trapezius and serratus anterior will result in abnormal movement of the scapula and a reduction in upward rotation of the glenoid fossa (Chester et al., 2010). The serratus anterior controlled the scapulothoracic joint, which provided a stable glenoid against which the humerus could rotate (Jobe et al., 1984). Increased downward rotation of the glenoid fossa will reduce the size of the subacromial area and could contribute to the development or persistence of SIS, potentially accounting for the longevity and chronic nature of SIS in the clinical setting (Chester et al., 2010). In 2010, Chester’s review of the impact of SIS on muscle activity patterns of the shoulder complex identified: three studies on onset muscle activation (Cools et al., 2003, Moraes et al., 2008, Wadsworth and Bullock-Saxton, 1997), two studies (Wadsworth and Bullock-Saxton, 1997) evaluated onset times on initiating bilateral scaption (abduction performed in the scapular plane) in standing and one study (Cools et al., 2003) evaluated onset during a reaction when the arm was suddenly and unexpectedly released from a passive support. Both Wadsworth and Bullock-Saxton (1997) and more recently Moraes et al. (2008), reported a greater variability in muscle activation for participants with painful shoulders in comparison with participants with healthy shoulders.

A current systematic review of the literature, by Struyf et al. (2014), failed to identify an established consensus on muscle scapular recruitment timing on patients with SIS. They concluded that patients with SIS also displayed numerous variations in scapulothoracic muscle activity, when compared to health controls. Two of their identified studies observed a consistent pattern of muscle recruitment timing (Moraes et al., 2008, Wadsworth and Bullock-Saxton, 1997). They suggested it started with an initial activation of the upper trapezius, followed by serratus anterior, middle trapezius and finally by the lower trapezius. However, the activation was independent of the presence of pathology. Measurement of the middle section of trapezius, indicated that there had not been any recruitment timing differences between SIS patients and controls (Moraes et al., 2008).

Therefore there was no consensus concerning the muscle recruitment timing in the various scapulothoracic muscles. There is extensive evidence on the altered scapular muscles activity in participants with SIS, however no evidence was found on the contribution of the glenohumeral muscles to the condition.

The impact of impingement on proprioception is also not clear. Haik et al. (2013), suggest that active joint positional sense is not altered in participants with impingement syndrome; however alterations were found in asymptomatic female assembly line workers exposed to overhead activities. The work of Haik, although in another field of investigation, suggested some similarities with the present study, mostly because it proposes to study participants in risk of the development of the condition, and participants with the condition (SIS patients). Haik's study, although with interesting findings, is not free from criticism, since they have chosen an IKD speed of 5º/sec instead of leaving the equipment unconstrained. This way, the participants could control the identification of the targeted positioning by controlling the time till achievement of the targeted angle.

Conversely, results from Haik et al. (2013), are not endorsed by Myers and Lephart (2000), who found in their review that after joint injury or fatigue, proprioceptive deficits were demonstrated, and neuromuscular control was altered. Anderson and Wee (2011b), have also investigated joint proprioception at higher shoulder elevations in chronic rotator cuff pathology, a condition related to the existence of shoulder joint impingement syndrome. They suggest that impairment of shoulder joint position sense in the chronic rotator cuff pathology group and that the degree of proprioceptive impairment was greatest at extreme degrees of elevation, with increased shoulder impingement and pain. Even though their study improves our understanding of the condition, the method is not repeatable. The participant being measured had their upper limb supported, whilst it was moved passively to the selected test position, using an angular velocity believed to be of approximately 60º/s. This protocol would be challenging to replicate at exactly 60º/s in every subject, and also the effect of the tactile cues was not adequately controlled.

Maenhout et al. (2012), investigated the impact of rotator cuff tendinopathy on proprioception, measuring force sensation. They found that regardless of the direction of the test, that patients overshot the target when compared to asymptomatic participants; however, no difference was found between the painful and asymptomatic side in patients. They suggested that overestimation of muscle forces, required for a given task, might further aggravate the symptoms and should be taken into account during rehabilitation. They chose 50% of the maximum voluntary contraction as targeted forces. This value is open to criticism, mostly because force reaction, as a proprioceptive skill relates to the ability to produce the appropriate amount of force required to stabilize the joint and produce the desired motion. Thus there is no necessity to develop great amount of force or torque, as 50% of the maximum voluntary contraction would be. This study was the only involving the measurement of force reaction in participants with impingement syndrome and no further comparison is possible.

There are two primary mechanistic theories that explain the specific fatigue-related kinematic changes that reduce the subacromial space. The first is superior migration of the humeral head and the second altered scapular kinematics (Chopp et al., 2010, Chopp et al., 2011), however more investigation is needed to further explore the causative factors of SIS.

In addition to the problems of classification discussed earlier in this chapter, there are also a number of other important methodological limitations in the literature. Many studies have adopted widely differing methodological and statistical approaches that make comparison and interpretation of findings difficult. There is considerable heterogeneity between studies with regard to the study setting, and both the characteristics and size of the population under investigation.

4.6 TREATMENT OPTIONS, REVIEW OF EFFICACY

Surgical and non-surgical strategies are used to treat SIS. The first-line management commonly includes conservative treatment, based on physiotherapy modalities, nonsteroidal anti-inflammatory drugs (NASAID), oral steroids and local injections of corticosteroids (Rabini et al., 2012). When rest, physical therapy and analgesics fail, local corticosteroid injections can be used to help relieve symptoms (Bell and Conaway, 2005). According to van der Sande et al. (2013), there is lack of evidence regarding the use of simple analgesics mild opioids or other commonly used NSAIDs for SIS and corticosteroid injections, suggesting that there is conflicting evidence for short and long-term effectiveness. This was further concurred by Jowett et al. (2013), who showed similar controversial results.

Dorrestijn et al. (2009), suggests that surgery has no better results on pain and shoulder function, than conservative treatment, with persistent defects and inadequate healing being reported (Cadet et al., 2012), mostly due to poor vascularization of the tendon. Dorrestijn suggested this following the review of a few low quality RCT studies that did not follow the PRISMA guidelines(Moher et al., 2009). A more recent review of systematic reviews, by Littlewood et al. (2013b), also concurred that surgery does not confer additional benefit over exercise alone or multimodal physiotherapy for rotator cuff tendinopathy and related conditions.

Conversely, exercise is considered to significantly enhance blood flow to the repaired rotator cuff (Cadet et al., 2012), which might suggest that targeted rehabilitation is the key to the treatment of the condition. Unfortunately, there is still a trend for an earlier referral for surgery (Haahr et al., 2005, Vitale et al., 2010). In fact, according to Feleus et al. (2008), patients with a non-specific diagnosis were more frequently referred to a physiotherapist, while patients with a specific diagnosis were more frequently referred to a medical specialist, especially the SIS group, with the largest referral rates. It might be suggested that the evidence from the physiotherapy literature is equivocal and needs further evidence to support practice.

Five systematic reviews exploring the effectiveness of physiotherapy and manual therapy on SIS have reported conflicting results (Gebremariam et al., 2013, Kuhn, 2009, Kromer et al., 2009, Michener et al., 2004, Desmeules et al., 2003). Desmeules et al. (2003), have reported limited evidence to support the efficacy of therapeutic exercise and manual therapy for SIS treatment. In a later review, Michener et al. (2004), reported limited evidence, with a tendency towards effectiveness of exercise, joint mobilization and laser therapy. Kromer et al. (2009), reported equal effectiveness of physiotherapist-led exercises compared with surgery in the long term and of home-based exercises compared with combined physiotherapy interventions in the short and long term. Kuhn (2009), reported that exercises had statistically and clinically significant effects on pain reduction and improving function, but not on range of motion or strength. He also added that manual therapy augments the effects of exercise; yet supervised exercise was not different than home exercise programs. Gebremariam et al. (2013), reported that moderate evidence was found for the effectiveness of hyperthermia compared to exercise therapy or ultrasound in the short term. Hyperthermia and exercise therapy were more effective in comparison to controls or placebo in the short term. In the midterm, exercise therapy appeared to give the best results compared to placebo or controls. Moreover, seminal authors (Littlewood and May, 2007, Littlewood, 2012, Littlewood et al., 2013a) have advocated the use of loaded therapeutic exercises to treat SIS and related conditions, under the assumption that tendons are mechanosensitive and so, capable of responding to mechanical stimuli, in which structured exercise programs might stimulate reeling, even under painful stimulation. However, it is not yet clear whether pain production, or avoidance, during exercise programs improve clinical outcomes (Littlewood et al., 2015). Additionally, resistance exercise appears to be an important component in these programs, though the literature is not yet clear on the preferable choice of exercise/group of related exercises, to treat this condition (Littlewood et al., 2015).

Nevertheless, for other interventions (like the manual therapy as an add-on therapy, laser or ultrasound and mobilization), inconclusive evidence was found. In general, all reviews reported that there is limited evidence, mostly evident from low quality studies, and so more research is needed before accepting their conclusions as evidence. Moreover, most of the reviews do not follow PRISMA recommendations (Moher et al., 2009) - (Gebremariam et al., 2013, Kuhn, 2009, Michener et al., 2004, Desmeules et al., 2003), one review (Desmeules et al., 2003) even included studies that did not clarify the existence of SIS in the sample, containing a portion of patients without SIS or used a sample of patients who were status post subacromial decompression surgery. Furthermore, the reviews from Desmeules et al. (2003) and Michener et al. (2004), only included studies of low to moderate methodological quality, since according to the resulting score from two independent reviewers, the included studies presented a mean methodological score of 13.9 ± 2.4 of 24 possible points (Desmeules et al., 2003) and a mean quality score of 37.6 out of a possible 69 points (Michener et al., 2004).

Aytar et al. (2015), aimed to analyze the effects of scapular mobilization on function, pain, range of motion, and satisfaction in patients with shoulder impingement syndrome (SIS). Although it could be questioned the reliability of the universal goniometer used to assess range of motion and the fact that application of therapeutic modalities and patient education in the three groups (mobilization, sham mobilization and therapeutic exercise) could have interfered in the outcome. In general however, the study was well developed (randomized, double blind, placebo-controlled clinical trial). Nevertheless the control procedure could be considered not to be the most appropriate and might have afforded some therapeutic effect, giving rise to false negative results. They have reported that there was no difference between groups. There was not a significant advantage of scapular mobilization for shoulder function, pain, range of motion, and satisfaction compared with a control or supervised-exercise groups in patients with SIS (Aytar et al., 2015). It might be that passive modalities of treatment are not targeting the core of this condition, mostly associated with motor control dysfunction and as a consequence, as stated byChester et al. (2010), more studies on the effect of therapeutically modalities targeting motor control are needed.

In a later review Dervey et al. (2014), studied the available literature on the effect of eccentric exercises as a treatment method for SIS, they have concluded that although there is some consensus in favor of the eccentric method, the current evidence is limited, inconclusive and more work is needed. Mostly the current studies fail to analyze the effect of the above mentioned regimen on the development of motor control strategies to overcome the situation.

While the available evidence seems to support the use of therapeutic exercise (Ludewig and Reynolds, 2009), the authors have outlined how improvements in effectiveness should be pursued, in order to develop a gold standard rehabilitation protocol. Current protocols have a lack of detailed description of the exercises included in the studies, demonstrate considerable clinical heterogeneity regarding interventions and outcome measures, small number of studies, and small sample sizes with short to no follow-up periods. All these factors may contribute to an overestimation of treatment effect. Nonetheless, motor learning strategies to normalize dysfunctional patterns of motion and strengthening the rotator cuff and scapular muscles were the key aspects in therapeutic exercise programs. Overall, the results suggested that rehabilitation of SIS patients is inconclusive and need further exploration. Most of the rehabilitation programs are based on the restoration of normal movement of the shoulder, even though little to no agreement exists on the literature regarding normal shoulder movement and muscle onset sequencing.

4.7 SUMMARY OF THE SHOULDER PATHOLOGY

An appropriate neuromuscular strategy is necessary to stabilize the shoulder complex during shoulder elevation. When the neuromuscular pattern is inappropriate, the shoulder could be at risk of developing SIS (Hebert et al., 2002).

Shoulder impingement syndrome (SIS) has been described as a mechanical compression of the rotator cuff tendons and subacromial bursa under the coracoacromial arch during arm elevation. Using the above assumptions, overhead activities involving repetitive arm movements in work and sports, have been identified as risk factors for developing SIS (Haik et al., 2013, Neer, 1972), mostly because trauma to tissues that contain mechanoreceptors may result in partial deafferentation, which can lead to proprioceptive deficits and susceptibility to re-injury becomes a possibility because of this decrease in proprioceptive feedback (Lephart et al., 1997).

A poorly functioning rotator cuff, alterations in the position of the scapula due to weakness of scapular stabilizer muscles, impaired scapulothoracic mobility, and tight pectoralis minor may increase anterior tilting of the scapula leading to effectively reduce the subacromial space and so producing a functional impingement (Severini et al., 2014). Although the evidence is clear on the involvement of the above mentioned conditions, the literature is less clear whether they are causative/etiological factors or consequence of the pathology.

SIS is a common condition across overhead workers, since functioning with the arms above shoulder level has been linked to biomechanical consequences such as increase in intramuscular pressure, impaired circulation, increased muscle activity and fatigue development. Therefore, correction of abnormal and restoration of correct motor control is imperative in the functional reeducation of shoulder impairments (Severini et al., 2014).

There is an outstanding amount of evidence suggesting the importance of the scapula and scapular muscles to the development of SIS, however there is a lack of evidence on the implications of altered glenohumeral motor control on the development of the condition.

Although SIS has been a well-documented pathology within the literature, the present review found few studies on proprioception (Anderson and Wee, 2011b, Maenhout et al., 2012, Haik et al., 2013) and motor control (Worsley et al., 2013, Larsen et al., 2013, Moraes et al., 2008) on patients with shoulder impingement syndrome.

Contrary to most of the articles on the topic, it is also acknowledged that any study on SIS patients should carefully analyze and sub-classify SIS patients depending on its underlying mechanism to enable better understanding of the pathological causes. Sub-classifying SIS patients depending on its underlying mechanism, such as that presented by Cools et al. (2008), and would be a better way to study the pathology.

CHAPTER V: JUSTIFICATION FOR THE CHOICE OF THE PROTOCOL

The available literature fails to identify normal patterns of shoulder motor control (Struyf et al., 2014), as a consequence of this, SIS treatment programs aiming to restore "normal" movement lack supporting evidence. Moreover, the choice of muscles to be targeted for SIS intervention is still controversial (Larsen et al., 2013, Moraes et al., 2008, Worsley et al., 2013, Wadsworth and Bullock-Saxton, 1997). The changes in motor control present in this group may represent a more global response, mainly due to the observation that both the injured and noninjured sides of the SIS patient groups displayed differences from the findings of the control group (Cools et al., 2003, Wadsworth and Bullock-Saxton, 1997, Diederichsen et al., 2009). Alternatively, it may be the result of local pain.

Furthermore, although there is evidence that altered patterns of upward rotation of the scapula may contribute to shoulder problems (Borstad and Ludewig, 2002, Ludewig and Cook, 2000, Ludewig and Reynolds, 2009), there is still a need for further investigation on the effect of glenohumeral muscles on the functional translation of the humeral head with decreased subacromial space. Chopp et al. (2011), suggest that the rotator cuff muscles, not the scapular stabilizers, have more influence on actively preventing mechanical subacromial impingement, and superior humeral head migration has been found to occur after a protocol designed to fatigue the rotator cuff, according to a radiographic analysis. However the topic remains controversial and more investigation is needed.

Repeated, sustained and high velocity overhead movements have been linked to the development of SIS (Chopp et al., 2010, Ellenbecker and Cools, 2010, Haik et al., 2013, Neer, 1972), although the implications for the glenohumeral muscles have yet to be fully explored.

In order to study normal shoulder motor control, it is necessary to evaluate patterns of muscle sequence, during functional movements in healthy participants. Since the overhead movement has been linked to the development of the condition and this patient group report pain due to subacromial impingement between 60 and 120º of shoulder elevation (Aytar et al., 2015), the study of elevation in the scapular plane may help elucidate the development of the condition. To explore this, a protocol of measurement needs to be developed and tested for internal, external validity and reliability. In order to do this the protocol was used in a population of normal healthy participants. The data from the normal studies will provide information concerning confidence intervals within which normal shoulder muscle function will lie. These data could then be compared to an equivalent data set from overhead sports participants and patients presenting with SIS.

Furthermore the study of shoulder proprioception is equivocal (Haik et al., 2013), however the literature suggest a decrease in the proprioceptive sense in this group of patients (Bandholm et al., 2006, Maenhout et al., 2012). This implies an increased possibility of re-injury if their sensorimotor system is not targeted during treatment.

In summary there is a lack of research identifying normal values for position sense and force reaction. In order to explore pathology normal values need to be determined using reliable and valid protocols.

The Isokinetic Dynamometer has been used in previous published research and is referred to as a gold standard measurement protocol (Dover and Powers, 2003). However within the published research there is insufficient consideration of the reliability and validity of the methods, which could compromise internal validity of the present study (Law and MacDermid, 2008).

To establish robust methods for measuring proprioception and motor control, the present study design has focused on developing protocols to improve the internal and external validity and reliability of measurement methods. In addition the variance of data from a normal healthy population has been established.

The internal validity of measurements was ensured through the design of this study. Concepts such as the learning effect of repeated testing leading to learning and fatigue, standardization of test methods, standardization of day, date and time, calibration of equipment, stability of the measurements, duration of rest periods, location of sensors and feedback during testing were all considered in the design of the protocol for this study. Heterogeneous sampling was used to improve the external validity of the findings. The sampling of the present study was a convenience sample that mirrored the

SIS sports injury population in terms of age, gender and activity levels. Furthermore, the choice of an unconstrained, functional movement for EMG evaluation improved external validity, because it mimics real life movements.

CHAPTER VI: EXPERIMENTAL WORKS

6.1 INTRODUCTION

A series of studies were undertaken to establish the reliability and the validity of the measurements, which included intratester test-retest reliability. The protocol also explored the most appropriate method for data processing, namely for the timing of muscle onset identification, since several methodologies have been described in the literature (for example visual inspection or mathematical criteria like the standard deviation above the rest mean) and the decision on whether to filter the data.

Pilot studies were considered necessary due to the lack of established methods concerning force reaction protocols and nor reliability studies measuring both position sense and force reaction (Dover and Powers, 2003). Moreover, there was little to no agreement found in the literature on normal muscle sequencing during the shoulder elevation, as previously discussed on the chapter 2.5.

The proprioceptive study and motor control study will be described separately. The proprioceptive study will explain the methodological considerations, report the IKD body of studies and discuss the main findings and considerations for the main study. The motor control study will detail the methodological considerations, the sEMG studies, discuss of the main findings and considerations for the main study.

6.2 PROPRIOCEPTIVE PILOT STUDIES

6.2.1 INTRODUCTION TO THE PROPRIOCEPTIVE PILOT STUDIES

There have been several methods described to measure shoulder proprioception, namely position sense, kinesthetic sense and force reaction, as detailed in chapter 3.1.1. Proprioceptive skills should address these 3 sub modalities (Aydin et al., 2001). However, the impracticalities of having to develop new equipment to measure kinesthetic sense (proposed by (Lephart et al., 1994) has resulted in the decision to focus only on positional sense and force reaction protocols.

Proprioceptive studies on positional sense have referred to both passive and active repositioning, however muscle thixotropy, the property of passive muscle that influences proprioception, is more prominent on the passive repositioning task (Proske and Gandevia, 2012). Moreover, active joint position assessment stimulates both joint and muscle mechanoreceptors and is a more functional assessment of afferent pathways (Lephart et al., 1997) and may as well better represent joint function than tests performed in the passive test mode (Aydin et al., 2001). On the strength of this evidence it was decided to only include active positional sense study.

There are other techniques that have been used to characterize proprioception, namely histological and neurophysiological methods (Jerosch and Prymka, 1996), inclinometers (Dover and Powers, 2003), goniometers, potentiometers, video and visual analogue scales (Riemann et al., 2002). However, the setup provided by the isokinetic machine is acknowledged to be an accepted and well established way to measure several aspects of the shoulder proprioception (Dover and Powers, 2003) and is referred to as a gold standard (May et al., 1997).

In order to establish robust methods of measuring proprioception, a series of studies were undertaken to establish the reliability of the measurements including intratester test-retest reliability or repeatability of measurements.

The Aims of the Study:

1. To establish normal patterns of proprioception in the shoulder

Objectives:

- I. To develop reliable methods to accurately measure proprioception of the shoulder joint
- II. To measure the variance in proprioceptive performance in a normal population

6.2.2 ISOKINETIC (IKD) EVALUATION

Isokinetic dynamometers provide constant velocity with accommodating resistance throughout a joint's range of motion (ROM) (Brown, 2000). This resistance is provided using an electric or hydraulic servo-controlled mechanism at a user-defined constant velocity (Drouin et al., 2004). The machine arm of the isokinetic dynamometer cannot be accelerated beyond the set velocity, since any force applied against the equipment results in an equal reaction force. The reaction force mirrors the force applied to the equipment throughout the range of movement of an exercise, making it theoretically possible for the muscle(s) to exert a continual, maximal force through the full range of motion (Brown, 2000).

The use of the isokinetic dynamometer has been widely used as a tool to both test and train individuals, patients and athletes (Brown, 2000). The technique can be used to evaluate both the function of a joint and the effectiveness of a therapy, mostly because objective parameters (e.g. muscle strength and range of motion) can be measured (Meeteren et al., 2002). Although, traditionally, the isokinetic dynamometer has been focused on the lower extremity, and in particular the knee joint, where it has been proved to have good reliability and standardization of test procedures (Sole et al., 2007, Keskula et al., 1995, de Araujo Ribeiro Alvares et al., 2014), more recently it has been used and studied in other joints (Wang et al., 2015, Noffal, 2003).

There is evidence of using the IKD in shoulder evaluation with excellent reliability (Meeteren et al., 2002). This test-retest reliability study in isokinetic muscle strength measurements of the shoulder found the Biodex dynamometer (Multi joint system 2) to have good to excellent reliability (ICC ranging between 0.69 and 0.92). In more recent work Edouards' et al. (2013), reported higher intraclass correlation coefficients for peak torque (0.87-0.97). The standard error of measurement ranged from 7.7 to 14.5% for peak torque and minimal detectable change ranged from 21.3 to 40.2% for peak torque measurements. The above mentioned results seem to suggest that the standard error of measurement and minimal detectable change reporting should be taken into consideration when evaluating the individual longitudinal changes in clinical practice.

Studies that consider the reliability of shoulder proprioceptive testing with the IKD machine: Voight et al. (1996), reported an intraclass correlation coefficients (ICC) for passive joint position sense repeatability of 0.95. No study was found for active joint position sense repeatability. (Dover and Powers, 2003), found that force reaction was reliably measured, with reported ICC of 0.981 for internal rotation and 0.978 for external rotation. The reported ICC was high, despite of the great amount of force (50% of the maximum voluntary contraction - MVC) that the participants had to perform.

As previously stated, force reaction as a proprioceptive skill, relates to the ability to produce the appropriate amount of force required to stabilize the joint and produce the desired motion. Maenhout et al. (2012), reported an ICC for force reaction of 0.849 for internal rotation and 0.909 for external rotation. However, they have reported the ICC using a non-standard calculation, since they have used the Cronbach's α as ICC statistics. They reported ICC, buy using the Cronbach's α test, for the determination of reliability. The Cronbach's α is the appropriate statistic for internal consistency of questionnaires and not for experimental studies (Bland and Altman, 1997). They also calculated the SEM, reporting 2.34 N for the internal rotation and 1.97N for the external rotation. However, SEM relies on the calculation of the ICC ($SD \times \sqrt{1} - ICC$), and in this case the ICC was not calculated properly. Therefore the results are spurious and the conclusions from this study questionable.

Other advantages of the IKD are the ability to isolate joints, generation of data that can be stored and used later, allow not only isometric, concentric and eccentric mode testing, but also proprioceptive testing. There are however, some disadvantages such as the cost of the equipment, the need for calibration and muscle actions are not specific to sports activities (Brown, 2000).

There are also several factors that can influence the reliability of the shoulder isokinetic evaluation: These include the kinematics of the shoulder joint and its extensive mobility (Edouard et al., 2011b) and the fact that there is no consensus about the localization of the functional joint axis of the shoulder, since the glenohumeral joint has an extensive range of motion in several planes and the axis of the glenohumeral joint moves about 8 cm in flexion/extension and abduction/adduction movements. The influence of this phenomenon on the reliability of the measurement results is unknown (Meeteren et al., 2002). Despite the fact that the use of the IKD is linked to several factors that can influence its reliability, it is a valuable choice for the measurement of proprioception because it enables evaluation of more than one type of proprioception skills (position sense and force reaction). Therefore it avoids problems associated with position sense evaluation with high velocity cameras, since for example in the work by Anderson and Wee (2011b), it was the examiner who supported the participant upper limb, moving it passively to the selected test position. This could have major implications on variability of tactile clues and angular velocities that can be avoided using the standardization procedure that the IKD machine provides. The IKD was originally used as the golden standard to establish the reliability of the inclinometer for the measurement of joint position sense (Dover et al., 2003). They also reported that measurement of force reproduction was reliably measured between days, revealing high temporal stability.

In summary, only three studies were found on reliability of shoulder proprioception, using the IKD machine. One of which cannot be used to draw conclusions (Maenhout et al., 2012) and the other two, one in joint position sense (Voight et al., 1996) and the other in force reaction (Dover and Powers, 2003), had only reported relative reliability coefficients. According to (Weir, 2005), the index of relative reliability should be accompanied by an absolute reliability index like the SEM and it is the aim of the present study to explore both relative and absolute reliability index. Furthermore, no study was found for active joint position sense repeatability.

6.2.3 METHODOLOGICAL CONSIDERATIONS FOR THE PROPRIOCEPTIVE STUDY WITH THE ISOKINETIC DYNAMOMETER

Although the assessment of joint position sense has become a common measure in research, no standard method for measurement has been established. Force reproduction is of particular interest in the shoulder because the glenohumeral joint primarily relies on dynamic restraints to maintain stability, however until now, this area of research has been neglected (Dover and Powers, 2003).

According to the same authors, earlier research has used a different number of trials, and it is unclear what the minimum number should be. Further some of the concerns in performing multiple trials include fatigue and a learning effect. This was an important consideration in the study design. Additionally, in order to avoid muscle fatigue, positional sense data collection was before force reaction. Any learning effect was studied *a posteriori*, using statistical testing and analysis.

In order for isokinetic test results to be accurate, regular calibration of the testing device is an important factor for consideration (Williamson et al., 1989). This way, daily calibration of the IKD machine was performed before commencing the tests.

The review of the literature has shown that IKD active position sense protocols indicate a good level of agreement, with all the literature reporting positioning of the participant with 90º of abduction and 90º of elbow flexion (Niessen et al., 2009, Myers et al., 1999, Dover and Powers, 2003, Aydin et al., 2001, Voight et al., 1996, Sterner et al., 1998, Kablan et al., 2004). Only Lee et al. (2003) and Haik et al. (2013), evaluated in a different plane, the scapular. The evidence indicates that the choice of the scapular plane enables a more functional approach of the movement. Similarly, there was a consistent choice of 40º anterior to the coronal or frontal plane in previously published literature (Borstad and Ludewig, 2002, Seitz and Uhl, 2012b, Szucs and Borstad, 2013).

There are, however, differences in the protocols for the target angles, which report some variability in published methodologies. Niessen et al. (2009), Sterner et al. (1998), Kablan et al. (2004) and Aydin et al. (2001), targeted midrange angles on their protocol, while Lee et al. (2003), chose midrange angle for internal rotation and end of range for external rotation. Myers et al. (1999), also chose midrange for internal rotation and end of range for external rotation, but added midrange angle for external rotation as well. Dover and Powers (2003) studied only end of range angles for both external and internal rotation, while Voight et al. (1996), only looked at values near the end of range for external rotation. Moreover, the tissue mechanoreceptors are activated by the level of tension and hence their activation level is expected to vary at different points in the ROM, as the tension in the tissues around the joint varies. Thus, the position sense may alter from one joint position to another (Kablan et al., 2004) and studies in these field should include both mid and end of range angles as targets. End of range provides information mostly on the proprioceptors present in the capsuloligamentous structures around the shoulder joint and the skin, since both become stretched. Additionally, passive stretch of a muscle also activates the muscle spindles embedded in the muscle, generating neural signals (Janwantanakul et al., 2001).

The significance of limb dominance has been explored in four studies; however none found proprioceptive alterations in relation to dominance (Aydin et al., 2001, Voight et al., 1996, Carpenter et al., 1998, Haik et al., 2013). This suggests that the choice of limb for evaluation is arbitrary and in the present study it has only been evaluated the dominant limb.

Force Reaction testing was evaluated using the isometric mode of the IKD. Although isokinetic assessment of shoulder internal and external rotator strength is commonly studied in many different postures (sitting, standing or supine) and shoulder positions (frontal or scapular plane with 45º or 90º of abduction), Dover and Powers (2003), performed a force-reproduction test with the participants standing. However, a systematic review by (Edouard et al., 2011a), suggested that the seated position with 45º of shoulder abduction in the scapular plane seemed the most reliable for internal rotation and external rotation strength assessment. This was used to inform the experimental protocol. Whilst 45º of shoulder abduction has been suggested (Edouard et al., 2011a), clinical practice would indicate that 90º would represent a more challenging position in SIS patients, with the possibility of reproducing symptoms. There is also the potential of applying this work into sporting populations and therefore the 90º position would replicate a functional activity for this group.

The protocol reported by Dover and Powers (2003) and Maenhout et al. (2012), involved participants initially performing the task with visual clues and then with the visual feedback removed. This protocol was also used to inform the methodological design of the research.

Dover and Powers (2003), used two target angles (90% of IR and 90% of ER on the isometric mode) and calculated the maximum voluntary isometric contraction (MVIC) for each, followed by a target force of 50% of the MVIC. The same protocol was used by Maenhout et al. (2012), which has already been evaluated in section (5.2.2). The rationale for the choice of targeted forces was that although the throwers shoulder experiences significantly higher isometric strength of shoulder external and internal rotation than the non-athletic group, the comparison of the internal and external rotation strength of the dominant side in each group showed that throwing athletes showed significantly lower isometric strength during external rotation of the shoulder compared to internal rotation, suggesting that adaptations occur during overhead sports practice

(Nodehi-Moghadam et al., 2013). Dover and Powers (2003), also reported significant differences in target-force for force reproduction testing, with higher values for IR than for ER target positions for healthy participants. Under the above assumptions, different targeted forces were chosen, with greater force for internal rotators. Since the aim is for the production of small amounts of force, in this study 10 N.m for internal rotators and 5 Nm for external rotators were chosen.

The choice of the angular velocity in IKD proprioceptive measurements of the shoulder joint is arbitrary, since low and high angular velocities are often used. The common assumption is that high angular velocity relates to muscle coordination which is important in functional activities (Meeteren et al., 2002). Described methodologies for positional sense varied between 0.5º/s (Niessen et al., 2009), 5º/s (Lee et al., 2003, Haik et al., 2013) and even 60º/s (Anderson and Wee, 2011b). However, during a volleyball match, in the acceleration phase of throwing, humeral internal rotation velocities will reach over approximately 4520 deg/sec (Wagner et al., 2014). These findings have implications in the present study in the choice of the IKD speed of 300º/sec for the position sense evaluation. Moreover, according to Anderson and Wee (2011b), higher velocities are also considered more consistent with most functional activities in the upper limb, particularly within sporting populations. A high speed was set in accordance with the published rationales, however participants were free to move at any speed within this set of parameter. There was therefore the possibility of moving at a slower speed during test.

6.2.4 CONSIDERATIONS FOR THE PROPRIOCEPTIVE STUDY

The sample size for the study was selected according to previous published data (Myers et al., 1999, Dover and Powers, 2003, Dover et al., 2003, Janwantanakul et al., 2001, Bradley et al., 2009, Roy et al., 2008, Lee et al., 2003). Myers et al. (1999) evaluated 32 physically active college students (16 males and 16 females), Dover and Powers (2003) assessed 31 participants (males and females), Nissen et al. (2013) evaluated 28 health participants, Aydin et al. (2001) evaluated 24 participants, Carpenter et al. (1998) and Sterner et al. (1998) studied 20 participants, while Lee et al. (2003) evaluated only 11. Based on the number of participants included in the previous studies and the possibility of drop outs, or misconduct during the trials; larger sample size was considered appropriate.

There is also increasing evidence suggesting that WHO body mass index (BMI) cut-off values are outdated and should not be applied to different population. To overcome misclassifications, direct measurements of percentage body fat (PBF) would be a better tool for preobesity and obesity diagnosis (De Lorenzo et al., 2011). Although screening for adiposity using direct methods (skin folds) constitutes a better method to identify obesity, the literature tends to stress its use mostly for identification of people at higher risk for cardio metabolic disturbances and cardiovascular mortality. Since this is not the scope of the present screening, and due to time constraints, direct measurement was avoided and BMI was used for exclusion of overweight participants, since obese participants seems to have compromised proprioceptive skills (Wang et al., 2008). All the measurements were made according to the International Standards for Anthropometric Assessment (Kinanthropometry, 2001).

The protocol also included assessment for ligamentous laxity through the positive thumb-forearm sign, observation of recurvatum of either elbow (without previous injury to elbow), or hyperextension of metacarpophalangeal joints, as proposed by several authors (Safran et al., 2001, Suprak, 2011). Pregnant participants were excluded from study, since peripheral joint laxity increases during pregnancy; however, these changes do not correlate well with maternal estradiol, progesterone, or relaxin levels (Marnach et al., 2003). Participants were excluded if they presented the above mentioned aspects mostly because there are some agreement in the literature on the deleterious effect of ligamentous laxity in the proprioceptive skills (Rozzi et al., 1999).

Other factors which influenced selection such as the presence of shoulder pathology, namely instability, calcification, fracture, capsulitis and surgery were also excluded because of the reported deleterious effect on proprioceptive skills and the lack of consensus in the literature on its effect on proprioception (Warner et al., 1996, Lephart et al., 1994, Aydin et al., 2001). There is no consensus within the literature on the effect of surgery on the proprioceptive mechanism of the shoulder. Aydin et al. (2001), reported no significant mean differences between surgically repaired and the contralateral shoulder of their sample. Conversely, Maier et al. (2012), in a much more recent and comprehensive study, reported decrease in shoulder joint proprioception after shoulder arthroplasty.

Neurological disorders were also excluded from study mostly because there is indication of failure to evaluate and to map proprioceptive information onto voluntary and reflexive motor commands such as in Parkinson's disease (Konczak et al., 2009). Stroke patients also showed both contralateral and ipsilateral shoulder threshold to detection of passive motion test impairment (Niessen et al., 2008). The authors suggest that the control of the muscle spindles and central integration or processing problems of the afferent signals provided by muscle spindles might cause these effects.

Vision can interfere with proprioceptive results (Sarlegna et al., 2009, Sarlegna and Sainburg, 2009), and therefore blindfolding of subjects recommended.

6.2.5 METHODS FOR THE IKD PILOT WORK

6.2.5.1 PARTICIPANTS

Ethical approval for all the studies was granted by the University of Brighton and also the Universidade Fernando Pessoa. All participants received information sheets and gave their written consent (see appendix 1).

All participants were healthy students from Universidade Fernando Pessoa, who were recruited via email. All the measurements were performed by the same examiner in order to reduce interrater variability.

After screening tests for exclusion criteria, 6 participants failed to follow force reaction protocol and were excluded from study. The final sample was composed of 32 participants for position sense and 26 participants for force reaction studies.

Joint Position Sense Study

Thirty-two right handed participants aged between 18 and 30 (mean=22.53, SD=3.44 years) were recruited (Table 1).

Table 1. Participant profiles in the joint position sense study, description of number of participants, age, stature, body mass and body mass index.

Participants	Total	Male	Female
N	32	16	16
Age (years)	22.53±3.44	23.19±2.80	21.88±2.28
Stature (m)	1.69±0.08	1.75±0.05	1.63±0.06
Body Mass (kg)	71.16±14.76	76.98±12.90	65.35±14.55
BMI (kg/m^2)	24.85±4.12	25.05±3.52	25.05±3.53

Legend: BMI – Body Mass Index

Force Reaction Study

Twenty-six right handed participates aged between 18 and 30 (mean=22.42, SD=3.29 years) were recruited (Table 2).

Table 2. Participant profiles in the force reaction study, description of number of participants, age, stature, body mass and body mass index.

Participants	Total	Male	Female
n	26	13	13
Age (years)	22.42±3.29	23.31±3.99	21.54±2.22
Stature (m)	1.68±0.09	1.75±0.05	1.62±0.06
Body Mass (kg)	69.71±13.85	78.68±13.56	60.75±6.43
BMI (kg/m^2)	24.43±3.36	25.62±3.60	23.24±2.73

Legend: BMI – Body Mass Index

Inclusion Criteria: Right-handed participants, between the ages of 18 and 30 years with no history of surgery or upper limb pathology.

Exclusion criteria: obesity, calcification or fracture; shoulder instability (positive sulcus and relocalisation tests); previous shoulder surgery; shoulder pain during neck movement, shoulder capsulitis and neurologic disorders. Generalized ligamentous laxity and pregnancy cases were excluded from study. The exclusion criteria were identified by screening tests and questions performed by the researcher at the time of the evaluation. Obesity was investigated using the Body Mass Index Formula.

6.2.5.2 MATERIALS

An Isokinetic dynamometer, Biodex System 4 Pro®, was used to collect both position sense and force reaction data. For further information on the system characteristics, please consult the manual (Biodex Multi-Joint System – Pro, Setup/Operation Manual). The use of a blindfold allowed the inhibition of visual clues. The instruments needed for BMI preassessment was the Stadiometer and Tanita Scale.

6.2.5.3 EXPERIMENTAL PROCEDURE

The body mass was measured without shoes, with the scale reading zero, then the subject stood on the center of the scales without support and with the weight distributed evenly on both feet. For the stretching stature protocol the subject stood with the feet together and the heels, buttocks and upper part of the back touching the scale. The head was placed in the Frankfurt plane that is achieved when the orbitale (lower edge of the eye socket) is in the same horizontal plane as the tragion (the notch superior to the tragus of the ear). When aligned, the vertex is the highest point on the skull. An upward pressure was transferred through the mastoid process and the subject was instructed to take and hold a deep breath. After placing the head board firmly down on the vertex, according the protocol proposed by the International Society for the Advancement of kinanthropometry (ISAK).

The participants were then asked to complete the sample characterization questionnaire (appendix 2).

The IKD machine was calibrated at the start of each data collection. The machine arm was adjusted and aligned with the plane of the scapula, which was taken to be 40 degrees anterior to the coronal plane. It was recorded by means of palpation of skeletal landmarks and conventional goniometry.

The seat of the isokinetic machine was adjusted to fit the subject and the straps were applied to ensure that the subject did not move in the seat during the procedure. The position of the seat and the height of the seat were adjusted to align the axis of the machine with the axis of the glenohumeral joint (Figure 2). Axis alignment was horizontal through the head of the shaft of the humerus in a 90º abduction mode. Dynamometer orientation was 20º, tilt 0º and seat orientation 45º. Attachments used were the elbow/shoulder attachment with cuff.

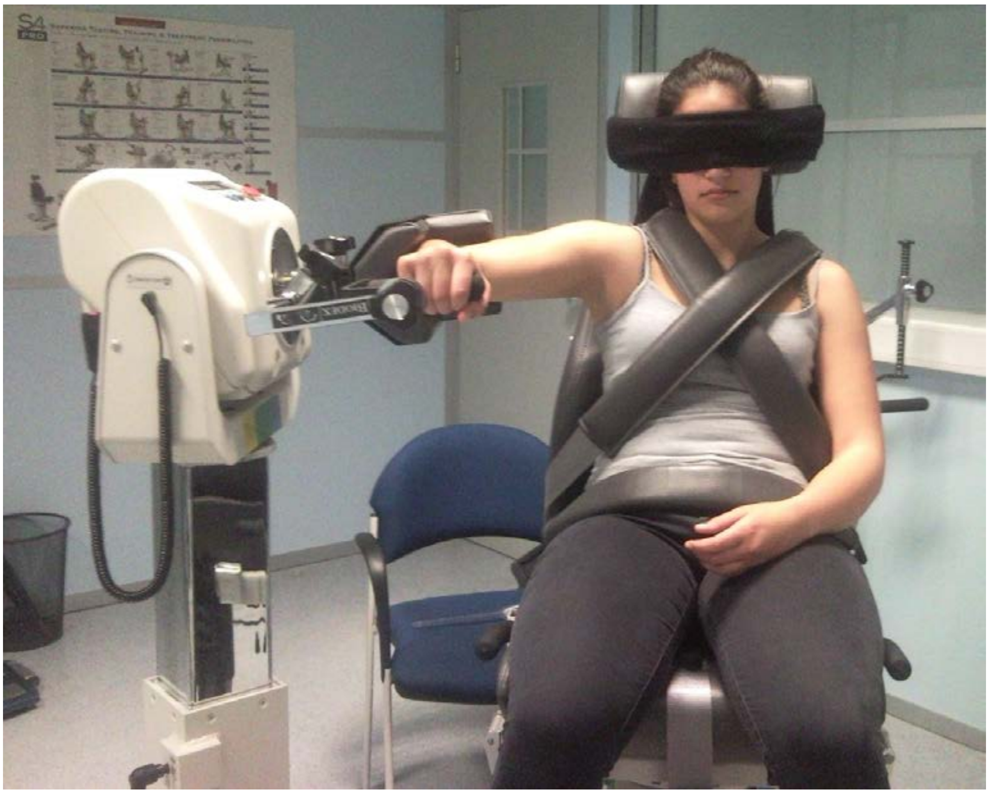


Figure 2. Proprioceptive Measurement Apparatus

The participants were blindfolded to remove visual clues. A spirit level was used to confirm the “zero” position on the isokinetic dynamometer. The target angles were chosen to represent both midrange and end range of motion (0º, 45º and 80º) and testing of joint positional sense (JPS) were measured prior to force reproduction (FR), since JPS has been described as being affected by fatigue.

Protocol to measure joint position sense (JPS)

In order to avoid fatigue, there was no warm up or preparation for the measurement. The participants were asked to wear a sleeveless t-shirt in order that the measurements could be undertaken without interference from clothing.

The chosen IKD protocol was proprioception unilateral, and the movement speed was set to 300º/s. The anatomical reference was 0º, attachment sensitivity 7-shoulder rotation and a rest time of 60s, cushion 1-hard, with a pattern of external/internal rotation, mode 90º of abduction.

Following positioning of each subject on the IKD machine, the stabilization belts were applied to avoid any compensatory movements. The movement and measurement procedure was explained to the subject before a blindfold was applied. The upper limb was secured with the elbow and hand IKD’s accessories. The participant was positioned in 90º of abduction (scapular plane), with full internal rotation, the elbow flexed (90º) and the arm fully pronated.

The range of motion was assessed for internal rotation (IR) and external rotation (ER) while the shoulder and elbow was maintained in 90° of abduction and flexion, respectively and scapular plane. The participants were instructed to actively rotate the arm to the endpoint of the range in both the IR and ER directions and ROM was verified. IKD ROM for every subject was selected from 30º of internal rotation to 110º of external rotation, total ROM of 140º. Then the position was calibrated to zero (using a level) and limb weight was specified.

The subject’s limb was positioned at target angle for integration of the position for 10 seconds. The participant was provided with a prompt phrase: “Please memorize this position”. The limb was then moved back to the starting position and the subject was then asked to move the limb back to the memorized position and to verbalize “YES” when they believed they had returned to the target angle. The prompt phrase used was: “Move the limb to the memorized position and say YES when you think you’re there”. The experimenter then recorded the position. The procedure was the repeated for twice more.

Protocol to measure force-reaction or force-reproduction (FR)

Force-reproduction testing was performed with the subject in the same position as described for the JPS protocol. All testing was performed with the dynamometer set to collect data in the isometric mode.

The angles remained the same as for JPS, although the number of repetitions was 4 per angle target. To begin the FR measurement the subject attempted to rotate the dynamometer arm internally while receiving visual feedback regarding the force being produced. The target torque was set at 10N.m. Once the subject achieved the target force, he was instructed to maintain it for 10 seconds and to concentrate on how much force was being exerted. The subject was instructed to relax for 5 seconds. The visual feedback was removed and the subject was instructed to reproduce the force without visual input. This protocol was repeated for each angle (0º, 45º and 80º) (in both internal and external rotation). For internal rotation the generated torque was set to 10N.m. while for external rotation the generated torque was set to 5N.m. in order to adjust to the natural difference between internal and external rotators.

6.2.5.4 DATA ANALYSIS

The data was analyzed on Microsoft Excel v.2010. The absolute error score for each trial and target angle was calculated, as the absolute difference between the target angle and the observed angle, for JPS, and the target force and the observed force, for FR. The data was then transferred to the statistical Package for the Social Sciences (version 20.0, SPSS Inc, Chicago, IL) and it was used to perform all statistical analyses. Apriori level of significance was set at $p \leq 0.05$.

The data were tested for distribution using the Kolmogorov-Smirnov test for the joint position sense data and using the Shapiro-Wilk for force reaction data (see appendix 7). The Mauchly test of sphericity was employed, and where the assumption of sphericity was violated, F ratios based on Greenhouse-Geisser correction were used.

Data that were normally distributed were analyzed using parametric tests and the data that was not normally distributed used non-parametric tests.

A repeated-measures analysis of variance was used to compare the angles and trials observed by the investigator for positional sense (normally distributed). Related samples Friedman's two-way analysis of variance by ranks was used to compare between angles and trials for the force reaction data (not normally distributed).

The coefficient of repeatability were calculated from the Bland and Altman formula (Bland and Altman, 1996a). The repeatability coefficient shows the limit which it is expected the differences between two measurements to lie (Bland and Altman, 1996b).

Intratester instrument reliability was determined using the intraclass correlation coefficient (ICC). To calculate within-visit reliability by having patients been examined 3 to 4 times, one-way random intra-class correlation coefficients, single measures for position sense data and average measures for force reaction data, together with their confidence intervals, were calculated with SPSS statistical software. To interpret ICC values it was used benchmarks suggested by Fleis and Shrout (>0.75 excellent reliability, 0.4‑0.75 fair to good reliability and <0.4 poor reliability) (Fleiss et al., 2003).

Descriptive statistics were used to define the study population and to calculate proprioception characteristics (see appendix 3).

6.2.6 RESULTS – JOINT POSITION SENSE

A. Normal Patterns of Position Sense

Objective: Establish normal patterns of position sense in the shoulder

The following table (Table 3) shows the proprioceptive responses in the shoulder of a population of people without pathology. Positional Sense data was calculated by subtracting the measured angle from the target angle (0, 45 and 80), to give the produced error, in order to allow between angle comparisons.

Table 3. Mean and Standard Deviation of the produced errors (in degrees) for each target angle (positional sense, 3 trials, *N*=32) and for all the measurements (total).

Target Angle	Mean Error	SD	Max underestimate	Max overestimate
0º	-2.19	3.70	-10.67	4.60
45º	-2.73	5.88	-13.73	11.67
80º	-0.45	5.91	-15.47	8.53
Total	-1.79	5.30	-15.47	11.67

Generally the participants, for all the angles, underestimate the reference, as can be seen in the following graphs. Since joint positional sense data was normally distributed, a one-way ANOVA test showed no statistically significant difference between angles ($F(2, 93)=1.646$, $p=0.198$). The following graphs (Figure 3) displays the mean measurement for each target angle with standard deviation bars.

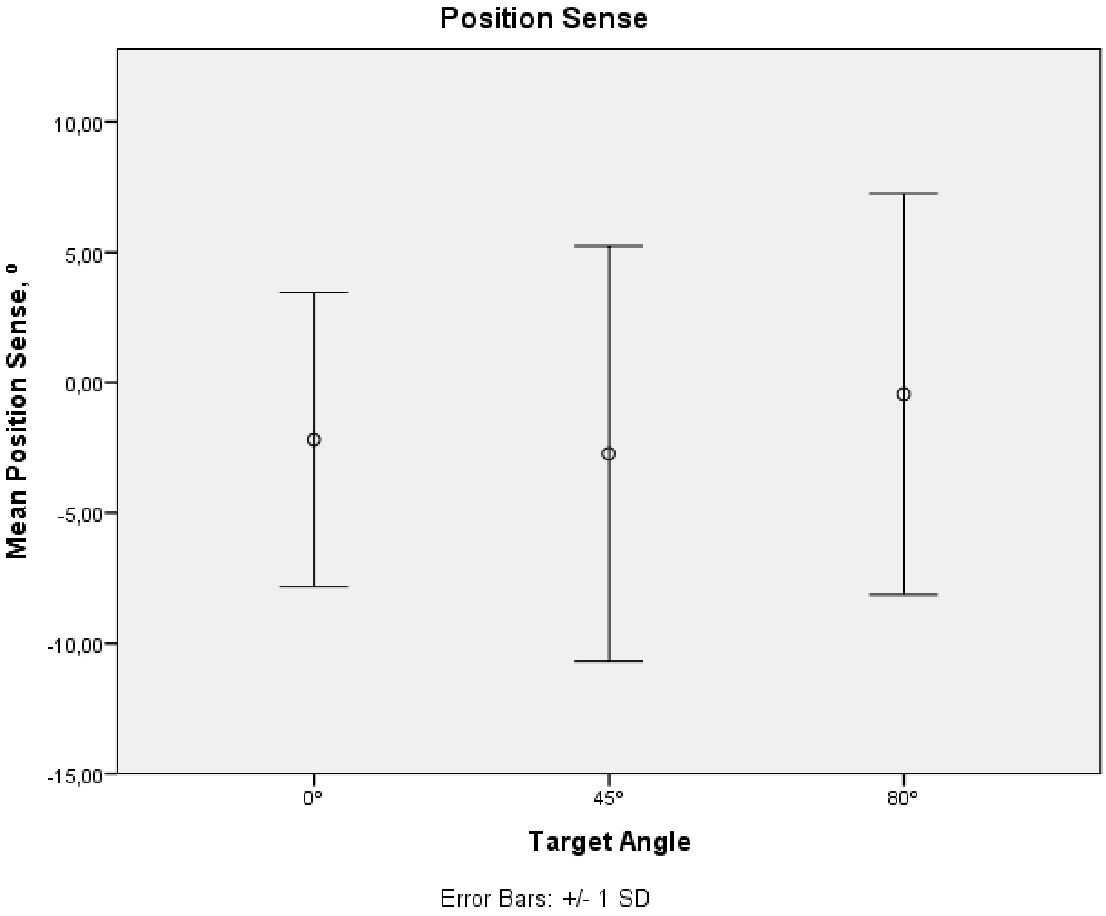


Figure 3. Position sense error, mean and standard deviation for each target angle.

B. Reliability of Measures of Position Sense

Objective: To assess the reliability of position sense measurements of the shoulder joint

The following table (

Table 4) shows the errors produced in each trial in the shoulder of a population of people without pathology.

Table 4. Positional Sense Mean and Standard Deviation (SD), in degrees, for each trial and the respective repeated measures ANOVA with significance, *p* value.

n=32	Mean Error (°)	SD (°)	ANOVA
Target angle 0. Trial 1	-3.90	5.93	(*F*(2,31) = 2.79, *p* = .07)
Target angle 0. Trial 2	-1.61	5.53	
Target angle 0. Trial 3	-1.07	5.21	
Target angle 45. Trial 1	-4.74	9.33	(*F*(2,31) = 2.90, *p* = .06)
Target angle 45. Trial 2	-2.57	7.22	
Target angle 45. Trial 3	-0.88	6.87	
Target angle 80. Trial 1	-1.01	7.61	(*F*(2,31) = 0.27, *p* = .76)
Target angle 80. Trial 2	-0.45	8.01	
Target angle 80. Trial 3	0.13	7.64	

The results from the above table suggests there were no differences between trials, as reported by the repeated measures ANOVA with within participants analysis of variance (one-way ANOVA), sphericity assumed.

The reliability of measures was tested using an intraclass correlation test (ICC), Table 5:

Table 5. One-way random intraclass-correlation coefficient, single measures and associated confidence intervals for position sense data.

Positional Sense	ICC	95% CI Lower Bound	95% CI Upper Bound
0°	0.14	-0.06	0.38
45°	0.31	0.10	0.54
80°	0.38	0.16	0.60

For 0°, the ICC(1,1)=0.14, with 95% CI(-0.06,0.38) represents low reliability, however it should be interpreted carefully because for target angle zero, the repetitions appear to be very similar, with a very small standard deviation, when compared to 45 and 80º, which might explain the low ICC, as will be explained in the discussion.

All the values are below 0.4, indicating poor to fair agreement (Fleiss et al., 2003),

C. Variance of Proprioceptive Function, Study of Repeatability

Objective: To measure the variance of proprioceptive function in a normal population

Bland and Altman coefficient of repeatability is reported in Table 6.

Table 6. Results of between trials repeatability –Bland and Altman coefficient of repeatability (B&A).

Positional Sense	B&A (º)
0º	14.49º
45º	18.31º
80º	16.84º

The Bland and Altman values indicate the level of variance within the data. Repeated measures of this data would be expected to lie within these limits. The implications of these values is that any meaningful differences between participant groups would have to exceed these values. For example, it could only be assumed to be a meaningful effect if the difference, for 45º, in position/reposition ability between two groups were greater than 18º.

6.2.7 RESULTS – FORCE REACTION

A. Normal Patterns of Force Reaction

Objective: Establish normal patterns of force reaction in the shoulder

The following table (Table 7) shows the proprioceptive responses in the shoulder of a population of people without pathology. Force reaction data was calculated by subtracting the produced torque from the target torque (10 N.m./toward and 5 N.m./away), to give the produced error, in order to allow between angle and between direction comparisons. The data was found not to be normally distributed and therefore non-parametric testing was employed.

Table 7. Median and interquartile range of the produced torque Error (in N.m.) for each target angle and direction (force reaction, 4 trials, *n*=26).

Direction/Angle	Median	Lower Quartile	Upper Quartile.	Max underestimate	Max overestimate
Toward 0º	0.21	-0.76	1.00	-1.71	2.38
Toward 45º	-0.34	-0.86	-0.08	-2.05	0.73
Toward 80º	-1.01	-1.69	-0.54	-2.61	1.48
Away 0º	-2.05	-2.92	-1.21	-3.59	0.70
Away 45º	-0.62	-1.51	0.41	-3.28	1.54
Away 80º	0.19	0.31	0.92	-0.87	5.00

Legend: Toward – internal rotation, Away – external rotation.

Generally the participants, for the majority of the angles/directions, underestimate the reference, as can be seen in the following graph (Figure 4). There is also a tendency toward greater error as the arm is moved further from the neutral position, for internal rotation, and the inverse for external rotation.

The following graph (Figure 4) displays the median and interquartile range of measurements for each target angle and direction.

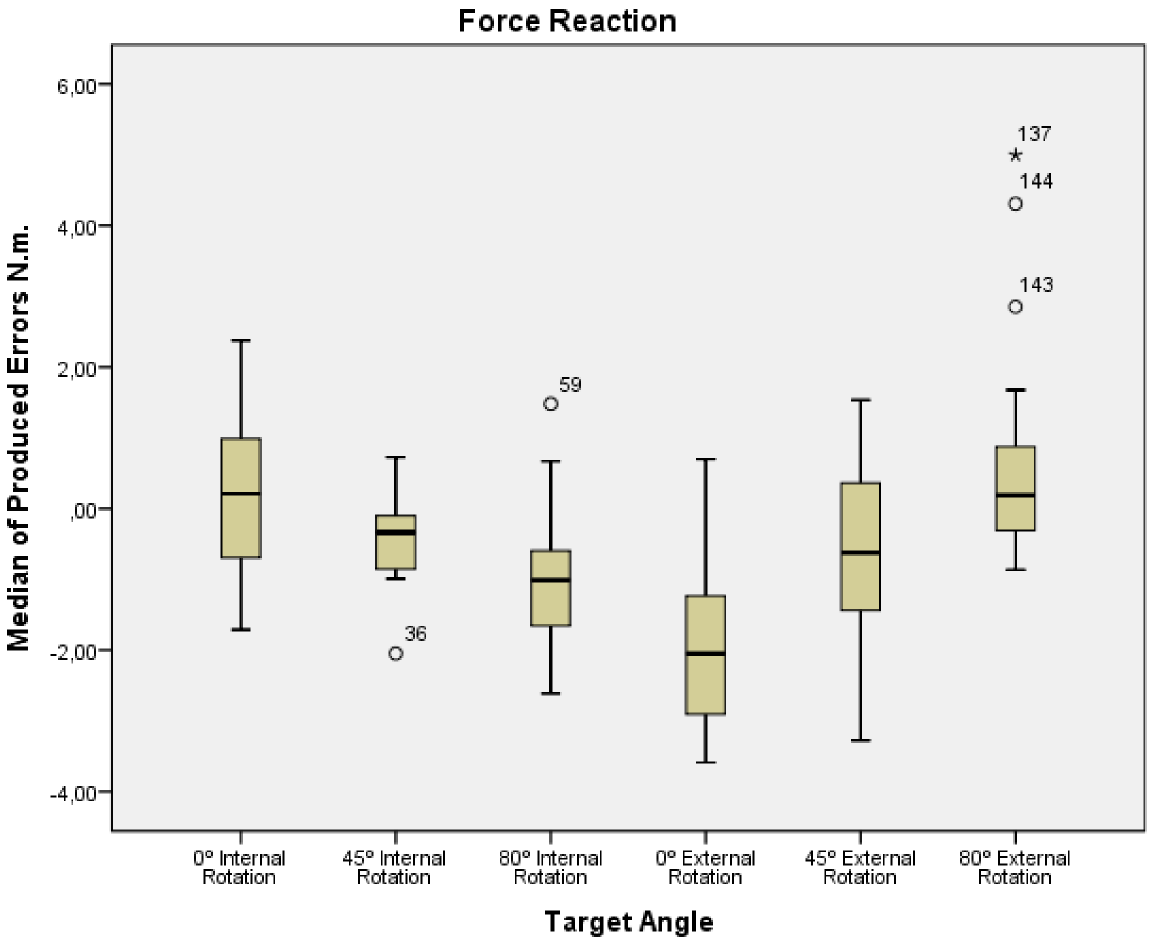


Figure 4. Boxplot representation for force reaction median and interquartile range, for each evaluated angle/direction.

Since force reaction data were not normally distributed, a Friedman's two way analysis of variance showed that there was a statistically significant difference in the produced errors depending on the angles and directions of movement $\chi^2(5) = 49.983$, $p = 0.001$. On the pairwise comparison there were significant differences between away and toward movements for zero degrees (p=0.001); between A0 and T45 (p=0.002), between A0 and A45 (p=0.001), between A0 and A80 (p=0.001), between T0 and T80 (p=0.017) and between both toward and away for 80º (p=0.001), as can be seen in Table 8.

Table 8. Pairwise comparisons, analysis of differences between target angles and directions (away – external rotation; toward – internal rotation).

Directions/Angles Pairs	Significance
Away 0º - Toward 80º	0.520
Away 0º - Toward 45º	0.002*
Away 0º - Away 45º	0.001*
Away 0º - Toward 0º	0.001*
Away 0º - Away 80º	0.001*
Toward 80º - Toward 45º	1.000
Toward 80º - Away 45º	1.000
Toward 80º - Toward 0º	0.017*
Toward 80º - Away 80º	0.001*
Toward 45º - Away 45º	1.000
Toward 45º - Toward 0º	1.000
Toward 45º - Away 80º	0.265
Away 45º - Toward 0º	1.000
Away 45º - Away 80º	0.392
Toward 0º - Away 80º	1.000

* Represents significance

No difference was found between 0º/45º and 45º/80º for internal rotation, however there was statistically significant differences between 0º and 80º. For external rotation, there was significant differences between 0º and 45º, no difference between 45º and 80º and statistically significant differences between 0º and 80º.

B. Reliability of Measures of Force Reaction

Objective: To assess reliability of force reaction measurements of the shoulder joint

The following table (Table 9) shows force reaction responses, in each trial, in the shoulder of a population of people without pathology.

Table 9. Force reaction median and interquartile range, in N.m., for each trial, both directions toward (internal rotation) and away (external rotation) and 0, 45 and 80 degrees. The Friedman's two –way analysis of variances by ranks for repeated measures were also calculated, and the significance reported (*p* value).

N=26	Trial	Median (N.m)	Lower Quartile	Upper Quartile	$\chi^2(2)$	*p*
Toward 0°	1st	-0.10	-0.22	0.13	2.42	0.490
	2nd	0.07	-0.84	1.16		
	3rd	0.25	-0.90	1.49		
	4th	0.57	-0.49	1.39		
Toward 45°	1st	-0.22	-0.42	-0.20	3.72	0.293
	2nd	-0.31	-0.61	0.26		
	3rd	-0.39	-1.26	-0.06		
	4th	-0.30	-1.13	-0.03		
Toward 80°	1st	-0.32	-0.47	-0.22	19.06	0.001*
	2nd	-0.60	-1.73	-0.33		
	3rd	-1.47	-2.20	-0.42		
	4th	-1.55	-2.22	-0.62		
Away 0°	1st	-0.85	-1.62	-0.42	19.99	0.001*
	2nd	-1.93	-3.28	-0.83		
	3rd	-2.29	-3.53	-1.43		
	4th	-2.53	-3.88	-1.80		
Away 45°	1st	-0.41	-0.88	-0.25	0.24	0.970
	2nd	-0.66	-1.66	0.83		
	3rd	-0.82	-2.04	0.78		
	4th	-0.77	-2.08	0.13		
Away 80°	1st	-0.16	-0.24	-0.11	12.09	0.007*
	2nd	0.03	-0.55	1.06		
	3rd	0.44	-0.33	1.87		
	4th	0.67	-0.055	1.56		

* Represents significance

Legend: Toward – internal rotation, Away – external rotation.

The Friedman's two –way analysis of variances by ranks for repeated measures, did not show any significant differences between trials for the 0º, toward, 45º, toward and away. For 80º both toward and away and 0º away there were significant differences between the trials (see the following table). The following table (Table 10) shows the pairwise comparisons for the differences between trials.

Table 10. Pairwise comparisons for the differences between trials observed for the Friedman's two-way analysis of variance by ranks for repeated measures.

Trials		Significance
80º Internal Rotation (Toward)		
1	2	0.976
	3	0.005*
	4	0.001*
2	3	0.319
	4	0.081
3	4	1.000
0º External Rotation (Away)		
1	2	0.319
	3	0.043*
	4	0.001*
2	3	1.000
	4	0.810
3	4	0.514
80º External Rotation (Away)		
1	2	1.000
	3	0.600
	4	0.016*
2	3	0.0,514
	4	0.190
3	4	1.000

* Represents significance

Table 10, indicates that for 80° toward, there were differences between the 1st and 3rd and 4th trials. For 0° away, there were differences between the 1st and 3rd and 4th trials. For the 80° away there were only differences between the 1st and 4th trial.

The reliability of the protocol was tested using intraclass correlation analysis (Table 11).

Table 11. One-way random intraclass-correlation coefficient, average measures and associated confidence intervals for force reaction data.

Force Reaction	ICC	95% CI Lower Bound	95% CI Upper Bound
Toward 0°	0.87	0.77	0.94
Toward 45°	0.82	0.67	0.91
Toward 80°	0.75	0.55	0.88
Away 0°	0.79	0.61	0.89
Away 45°	0.77	0.58	0.89
Away 80°	0.82	0.68	0.91

In general and according to Fleiss et al. (2003), all the ICC values are classified as excellent (higher than 0.75) representing excellent agreement beyond chance. The force reaction data collected using the IKD dynamometer demonstrated excellent reliability, beyond chance.

C. Variance of Force Reaction Data, Study of Repeatability

Objective: To measure the variance of force reaction data in a normal population

Bland and Altman coefficient of repeatability is reported in the following table (Table 12).

Table 12. Results of between trials repeatability – Bland and Altman coefficient of repeatability (B&A).

Force Reaction	B&A (N.m)
Toward 0º	2.23
Toward 45º	1.42
Toward 80º	2.61
Away 0º	3.06
Away 45º	3.46
Away 80º	3.37

At 0 degrees, for the movement of internal rotation, the difference between two measurements for the same subject is expected to be less than 2.23N.m. This results indicates that any single result will lie within a confidence interval of 2.23N.m. Similarly, at 45 degrees, for the movement of internal rotation, the difference between two measurements for the same subject is expected to be less than 1.42N.m. At 80 degrees, for the movement of internal rotation, the difference between two measurements for the same subject is expected to be less than 2.61N.m.

At 0 degrees, for the movement of external rotation, the difference between two measurements for the same subject is expected to be less than 3.06N.m. At 45 degrees, for the movement of external rotation, the difference between two measurements for the same subject is expected to be less than 3.46N.m. At 80 degrees, for the movement of external rotation, the difference between two measurements for the same subject is expected to be less than 3.37N.m. In terms of precision, the toward direction (internal rotation) evaluations are much more precise, since the repeatability values are around 20% of the target torque (10 N.m), while for external rotation the percentage is much higher (around 60%) of the target torque (5 N.m).

6.2.8 DISCUSSION

The position sense protocols indicated that there were no significant differences between the scores measured at 0, 45 and 80º. In the present study, participants also demonstrated a tendency to underestimate the target angle. Janwantanakul et al. (2001), found that shoulder acuity was greater at the extreme ROM, in position sense protocols. Felli et al. (2012), stated that the tension on the capsuloligamentous complex play an important role on proprioceptive sense when the joint approaches the end of movement. Thus, an increase in the contribution of capsuloligamentous structures to shoulder proprioceptive sense at the extreme positions may improve accuracy. Janwantanakul et al. (2001), also indicated that when a joint approaches the limit of movement, increased stretch of antagonist muscles and tension in the tendons of agonist muscles and causes an increase in discharge of muscle spindles and Golgi tendon organs. The results from the present study are not in agreement with these previous findings, nor with the study of Kablan et al. (2004). This might be related to the fact that the proprioceptive protocol, for the present study, didn't include extreme end of range angles. Future protocols may need to allow further comparisons between normal subjects and patients with SIS. The choice of 80^o, as an extreme range of motion angle for evaluation, had the aim to allow extreme range of motion measurements, however not extreme enough to produce discomfort to the participants with pathology.

The present study also did not show significant differences between trials for position sense measurement. Analysis of each trial did not seem to support a learning tendency in the data from the 1st to the 3rd measurement, meaning that the replication protocol (3 trials) wasn't enough to produce learning bias, since it would be expected a consistent reduction on the amplitude of the errors, which wasn't seen in trials analysis and a significant difference between trials which wasn't observed on the analysis of variance. This fact could suggest that one trial would be enough to measure joint position sense. Mostly because fewer replications are needed if a response variable changes little from one measurement to the next. However, since the reliability of assessment is fundamental to track small but clinically relevant changes (Edouard et al., 2013) and the present study showed fair to poor ICCs, to improve reliability in shoulder measurements, additional measures will be considered and a more constrained setting.

The main problem with ICC correlation is that the value of the correlation is sensitive to the heterogeneity (spread) of values between participants (Hopkins, 2000). Thus, it is not possible to compare the reliability of 2 measures on the basis of their retest correlations alone: the worse measure (the one with the larger typical error) could have a higher retest correlation if its reliability was determined with a more heterogeneous sample. The retest correlation is only useful when the value calculate is interpreted in light of the variance of the population from which the data is taken.

The present study only at 80º the ICC was near the limit of fair to good classification proposed by Fleiss et al. (2003), and yet, in light of the variance present in the data, it would be plausible not to consider it as a good value. Furthermore, The low reliability of positional sense could be a result of the difficulty in controlling the various degrees of freedom of the shoulder (Edouard et al., 2011b). Moreover, the angle of shoulder abduction could also have an influence on reliability, since lower reliability was reported in isokinetic assessment of muscle strength using 90º of shoulder abduction (Kimura et al., 1996). However, this position was chosen because future protocols could include SIS patients, and it would be important to analyze how their proprioceptive system works at a more challenging position of the shoulder.

Whereas agreement between repeated measurements is a characteristic of the method or instrument, reliability (ICC) depends on both the magnitude of measurement errors and the true heterogeneity in the population in which measurements are made (Bartlett and Frost, 2008). This way, the general form of the ICC is a ratio of variance due to differences between participants to the total variability in the data and it has been a subject of criticism for the use of ICC alone. To avoid this problem, this index of relative reliability should be accompanied by an absolute index (Weir, 2005). Looking at the descriptive statistics of the present results, for 0 degrees there is less variation between repetitions than for 45 and 80 degrees, which is the opposite of the ICC results, which might be supportive of the knowledge that ICC's can be skewed by the presence of heterogeneity in the data.

The repeatability coefficient shows the limit which it is expected the differences between two measurements from the same subject to lie (Bland and Altman, 1996a). The repeatability coefficient has ranged from 14.49º to 18.31º. The poor repeatability present in the data might be related with the decision to use 300º/s velocity, to have an unconstrained speed of movement for position sense evaluation. With all the other studies choosing to use lower velocities it seems plausible that its choice could reduce the errors and improve repeatability. However, it should be considered the fact that using small velocities, like in the study of Haik et al. (2013), the authors have chosen an IKD speed of 5º/s and the participants could control the identification of the targeted positioning by controlling the time till achievement of the targeted angle and it did not represent a functional movement (Anderson and Wee, 2011b). Under the above mentioned circumstances, it seems plausible to slightly constrain the speed of the isokinetic machine for the position sense protocol on the final study.

Furthermore, according to Suprak (2011), shoulder joint position sense is only enhanced as the joint approaches end range of motion in studies involving internal and external rotation with the arm supported, but this finding has not been confirmed in unconstrained movements. In fact in their unconstrained movement they have found that there were no differences in either absolute or variable errors were observed between positions. These results not only further support the findings from the present study, since there are no differences between ROM positions, but also suggest that the measurement setting might have been able to reproduce the nature of the unconstrained movement. These findings also corroborate the possibility that muscle spindles are a dominant source of afferent feedback regarding shoulder joint position sense in unconstrained movements, even approaching end ROM, when the capsuloligamentous receptors are active.

For force reaction, it was found significant statistical differences between directions and angles. Generally, there were more errors for external rotation, when compared to internal rotation and a tendency towards increased force reaction errors with increased angle, for internal rotators, and decrease error with increased angle for external rotators. Generally the participants underestimated the reference (4 out of 6 direction/angles). These results are endorsed by Maenhout et al. (2012), whose results also suggest that healthy participants underestimate the target. They have also reported that errors were significantly larger during external rotation tests, compared to internal rotation and these results were similar to ours. The authors suggested that the relationship between a muscle’s length and its isometric tension generating capacity depends on the degree of overlap between its actin and myosin filaments. Muscle length is, therefore, capable of influencing force matching acuity.

Conversely, Kablan et al. (2004), suggested that the shoulders were more sensitive to external rotation than to internal rotation, because of a relative tightening of the capsular ligaments and activation of rotator cuff muscles. These studies indicated that internal rotation, from the externally rotated position toward the neutral position, relaxed the capsule and rotator cuff muscle, producing larger amount of errors.

Furthermore, the present study results also show decrease in error with increased angle for external rotators. As previously explained, according to Janwantanakul et al. (2001), when a joint approaches the limit of movement, increased stretch of antagonist muscles and tension in the tendons of agonist muscles causes an increase in discharge of muscle spindles and Golgi tendon organs.

According to Hopkins (2000), in tests of human performance that depend on effort or motivation, volunteers might also perform the second trial better because they want to improve. Performance can be worse in a second trial if fatigue from the first trial is present at the time of the second trial. Performance can also decline in a series of trials, owing to loss of motivation. This could partially explain the existence of differences between the first and the other trials, found in some of the evaluated angles/directions. It could be speculated that these results occurred because of the proximity with the familiarization protocol, with visual input. It is suggested that in future protocols the first trial should be discarded from analysis.

The participants of the sample mostly underestimated the target, which was in accordance with previous findings on force reaction protocols (Maenhout et al., 2012) and shows a tendency for health participants to underestimate the target, whereas participants with pathology often overshoot it.

Hopkins (2000), suggests that systematic change in the mean is a non-random change in the value between 2 trials that applies to all study participants. The simplest example of a systematic change is a learning effect or training effect: the participants perform the second trial better than the first, because they benefit from the experience of the first trial. The present study did not show any learning tendencies, perhaps because, as explained by the author, performance of practice trials helps reduce learning effects.

The ICC was excellent for all the evaluated angles, according the classification proposed by Fleiss et al. (2003). This result is endorsed by Maenhout et al. (2012) and Dover et al. (2003), since both studies reported excellent reliability for force reaction measurement and when compared, the present study reported smaller errors of measurement.

The difference between ICC values from positional sense data and force reaction could be explained by differences between samples, where samples containing participants who differ greatly will produce larger correlation coefficients than will samples containing similar participants (Bland and Altman, 1996c, Atkinson and Nevill, 1998). Atkinson and Nevill discuss this item even further and states that the ICC is affected by sample heterogeneity to such a degree that a high correlation may still mean unacceptable measurement error for some analytical goals. This way, they support the use of ICC but believe it should not be employed as the sole statistic and more work is needed to define acceptable ICCs.

The repeatability coefficient has ranged from 1,42N.m to 3,46N.m, showing good repeatability of the testing procedures.

Moreover, the design of this study was appropriate to allow identification of both absolute and relative reliability.

Limitations

The aim was to test for repeatability, with trials being conducted over a relatively short time frame. Therefore the temporal stability of the method for longer reassessment timeframes wasn’t tested on the present study. The inability to randomize the order of joint position sense and force reaction testing was another limitation. The randomization was not possible in virtue of the effect of fatigue on both proprioceptive tasks. Since joint position sense is less strenuous, it was performed first. However, if fatigue had been present, it would have been seen an increase in error scores from trial 1 to trial 3. Nevertheless, it is suggested that conducting the joint position sense before any muscle contractions provide the ideal method.

6.2.9 CONCLUSIONS

Position Sense summary of findings: There were no differences between trials; there were no differences between 0º, 45º and 80º for positional sense outcome, which corroborate the fact that muscle spindles are a dominant source of afferent feedback in unconstrained movements, even approaching end ROM, when the capsuloligamentous receptors are active. There were no tendencies for greater or smaller error with increase of the angle and all participants underestimated the reference. Though the relative reliability was low, possibly due to absence of variability between participants and the nature of the unconstrained movement. Future research should have into consideration a more constrained velocity for this measurement.

Force Reaction summary of findings: The participants underestimated the target and errors were significantly larger during external rotation tests, although the amount of errors decreased with the increase in the angle of external rotation. There were differences only between the first and the subsequent trials for toward direction at 80º, away direction for 0º and 80º, due to the proximity with the familiarization protocol, and there were no learning tendencies between trials. The ICC was excellent, however Bland & Altman coefficients of repeatability were greater for internal rotators when compared to external rotators.

6.3 SHOULDER MOTOR CONTROL PILOT STUDIES

6.3.1 INTRODUCTION TO THE SHOULDER MOTOR CONTROL PILOT STUDIES

There is only one published study on reliability of EMG measurements of shoulder motor control (Seitz and Uhl, 2012b). This study has only analyzed the following muscles: anterior deltoid, upper trapezius lower trapezius and serratus muscles. Therefore, in order to test whether this method of measuring motor control around the shoulder was sufficiently robust, a series of studies were undertaken to establish the validity and reliability of the measurements including intratester test-retest reliability or repeatability of measurements.

The Aims of the Study:

1. To establish normal patterns of shoulder motor control

Objectives:

I. To develop reliable methods to measure shoulder motor control
II. To validate the methods designed to measure motor control
III. To measure the natural variance in shoulder motor control

6.3.2 SURFACE ELECTROMYOGRAPHY SEMG EVALUATION

Objective measurement is a constant need in medicine, namely for quantification of physical and cognitive function as a basis or diagnosis. The body may be considered as an electrical system, measurement and quantification of which provides means for objective measurement of health status (Reilly and Lee, 2010).

The term electrogram is a Greek term, in which electro means electricity and gram meaning write or record and represents the definition of the recording of electrical signal from the body (Reilly and Lee, 2010).

Electromyography, a form of biomedical electrogram, is defined as the study of the electrical currents generated in a muscle during its contraction, providing data describing the neuromuscular activity (Yousefi and Hamilton-Wright, 2014, Reaz et al., 2006).

An electromyogram encodes information about the active motor units within its (Wakeling, 2009) detection zone (Wakeling, 2009). The electrical activity in muscle can be recorded with electrodes placed over the skin. The resulting sEMG is the sum of the action potentials generated by the motor units and filtered by the volume conductor (Farina et al., 2002). Volume conduction effects occur through the soft tissue between the bioelectric source and the recording electrodes. sEMG is a non-invasive tool, that reflects the algebraic sum of muscle action potentials passing beneath the recording electrodes (Cooper et al., 2014) and it is also a field specializing in the use of electronic devices to measure the energy of the muscles, to analyze the data, and to display the results (Criswell, 2011). sEMG has been widely used for analysis of muscular function in both normal and injured participants (Herrington and Horsley, 2009, Ludewig and Cook, 2000a).

According to Criswell (2011), the use of sEMG has many advantages, because it provides a safe, non-invasive and easy method for objective quantification of the energy of the muscle. The sEMG traces provide information to clinicians and researchers about muscle function and dysfunction.

Despite its numerous advantages, one limitation of the sEMG is that it identifies only a small proportion of the active units and these tend to be located superficially in the muscle. Nevertheless, sEMG allows accurate detection of relative changes in neural activation (Farina et al., 2010). There are other techniques which have been described to identify muscle activation, namely phase contrast magnetic resonance imaging and real-time ultrasound (Wen et al., 2008, Finni et al., 2006, Van et al., 2006), though they do not currently have the ability to accurately measure the small changes in timing (Crow et al., 2011).

Seitz and Uhl (2012b), studied both the intersession and intrasession reliability of muscle onset times of scapular muscle activity and found it to be highly reliable (within session reliability of muscle onset times was ICC=0.88-0.97), however between session reliability was lower with ICC=0.43-0.73. The threshold used however, was of >10% of

MVIC beyond resting activity to determine muscle onset timing during the concentric phase elevation. The 10% of MVIC is an estimate that is not free from criticism, first because the MVIC alone can be biased for example from lack of participants motivation, meaning that it is recognized that the method is not guaranteed to be able to reveal how active a muscle is in relation to its maximal activation capacity (Burden, 2010). Currently this is the only study that has investigated reliability of EMG onset in the shoulder joint.

In conclusion, the electromyogram, using simple electrodes on the surface of the overlying skin, is able to represent the relative timing and amplitude of muscular patterns recorded, which reflects the aggregated activity of motor neurons that innervate each muscle and the motor fibres that are activated by them (Kandel et al., 2013). Electromyographic signals are valuable for studying motor control and for diagnosing pathology in the motor systems and in the muscles themselves, though more work is required to investigate the reliability of onset timing of shoulder muscles using the sEMG.

6.3.3 EMG PROCESSING AND ONSET DETECTION

Motor control analyzed through electromyography (EMG) provides information on initiation, cessation and magnitude of muscle activity, with 3 fundamental types of variables arising from the EMG trace: onset, amplitude and cessation (Riemann et al., 2002).

The signal recorded by sEMG contains the signal, which originated in the muscle being measured and noise components. Noise components may be intrinsic or extrinsic and can result in flawed interpretations, especially during dynamic contractions (De Luca et al., 2010).

The power line noise and the cable motion artefact are two extrinsic noise sources that modern technology and appropriate circuit design can eliminate totally (De Luca et al., 2010, Ruben, 2012). Intrinsic noise sources originate in the electronics of the amplification system (thermal noise) and at the skin-electrode interface (electro-chemical noise) (Huigen et al., 2002). Intrinsic and extrinsic noise sources form the baseline noise, detected when a sensor is attached to the skin. The movement artefact noise also originates at the electrode-skin interface and results from muscle movement under the skin and from movements at the electrode-skin interface (De Luca et al., 2010).

Soderberg and Knutson (2000) presented a guide for the use and interpretation of kinesiologic electromyography data, identifying 4 major steps; collecting, managing, normalizing and analyzing data. Data management can be done using raw or processed signals and demands decision making relative to data filtering. Regardless, the authors consider that raw data is the most fundamental and that using this type of data is an underused technique. Conversely, according to De Luca et al. (2010), filtering the maximum amount of noise contained in the electromyographic data increases the fidelity of the signal, while retaining as much of the desired electromyographic data as possible. If decision to include filtering as a process is made, Marletti (Hermens et al., 1999, Merletti and Hermens, 2000) regarding the standards for reporting EMG data, endorsed by the International Society Electrophysiology and Kinesiology (ISEK), suggests that filtering of the EMG should be specified by the filter type (e.g. Butterworth), low and/or high pass cut-off frequencies and slopes of the cut offs.

De Luca et al. (2010), suggests that low pass filter frequency should be set where the amplitude of the noise components exceeds the amplitude of the electromyographic signal, being preferably a low pass frequency in the range of 400-450Hz. The high pass filter frequency however, is more complicated due to the several sources of noise contributing to the recorded electromyographic signal. This has resulted in several recommendations and standards being reported. The original recommendation of ISEK recommended a high pass corner frequency of 20Hz (A. et al., 1980), Later work, endorsed by ISEK suggest a frequency of 5 Hz (Merletti and Hermens, 2000, Hermens et al., 1999). The Journal of Electromyography and Kinesiology proposes a corner frequency of 10Hz, and the Surface EMG for Noninvasive Assessment of Muscles (SENIAM) recommendations recommends 10-20Hz(Hermens et al., 1999).

Kamen and Gabriel (2010), suggest that movement artifact in the EMG signal is a potential problem during rapid movements only. Movements performed slowly are not considered a major problem, avoiding high-pass filtering.

Apart from filtering, there are several other levels of processing and analysis that can be performed in the sEMG data. The timing of muscle onset is an indicator of motor control, that has been described on the literature (Wong, 2009). The timing of muscle onset corresponds to the point in the electromyogram where the beginning of the contraction is identified.

Sometimes this activation occurs in a feed-forward manner, that is, an anticipatory muscle activation that occurs prior to the actual perturbation of balance. It is hypothesized that a deficit in a feed-forward activation increases the susceptibility of injury (Vasseljen et al., 2012).

The onset of EMG activity is usually identified on the basis of the earliest rise in EMG activity beyond the steady state (Kamen and Gabriel, 2010).

Numerous algorithms have been used to identify the onset of EMG. The “traumatic ocular” or visual inspection is the basis of analysis. The technique is based on the ability to “eyeball” the point at which the EMG signal exceeds baseline (Kamen and Gabriel, 2010), it is one of the basic procedures to find onset and a still defended method for some authors (Larsen et al., 2013, Worsley et al., 2013, Wickham et al., 2010). While other authors have suggested the usage of a percentage above maximum voluntary contraction (Seitz and Uhl, 2012b), others identify multiples of the standard deviation estimate above a baseline (Wattanaprakornkul et al., 2011, O'Connell et al., 2006, Szucs and Borstad, 2013, Baur et al., 2011). Neptune et al. (1997), used not just a multiple of the standard deviation above baseline (in this case 3STD’s) but also a temporal parameter (in this case stability of 50ms).

Interpretation of EMG data normalized to %MVC, have been referred to as improper, since participants with SIS cannot or do not fully activate their muscles during the normalization contraction, whether because of pain, inhibitory mechanisms, or avoidance, then %MVC values may be affected, as the 100% levels are not true maximal values and when comparing to normal groups it could be a confounding factor, inflating the SIS normalized EMG levels during functional activity (Chester et al., 2010). The choice of the onset method should have these considerations into account, additionally, since the traumatic ocular is very time consuming for a large set of data, The identification of a mathematical algorithm that might recognize small changes in the electromyogram might be the best available solution.

Some procedures may even require more complex techniques to assess onset timing. Santello and McDonagh (1998), proposed an algorithm that identifies muscle onset timing and involved full wave rectification of the signal and a continuous integration of all EMG data.

In summary, there is poor agreement on how to implement EMG filtering and muscle onset detection in the literature. Therefore, for each study, an individual approach should be developed to determine the appropriate method to be employed to process the data and determine onset.

A preliminary study was carried out to determine the data processing protocol.

6.3.4 CONSIDERATIONS FOR THE EMG PILOT WORK

When recording sEMG, the sensors need to be carefully and accurately placed on the muscle. The term sensor has been described as the ensemble of electrodes, electrode construction and (if applicable) the integrated pre-amplifier. The sensor type can either be monopolar, bipolar or array. The shape can be circular, oval, square, rectangular, or pin-shaped. The size may vary from a surface of 1 mm^2 to a diameter of several cm and the inter electrode distance from 1mm to several cm. Different types of electrode material can be used, ranging from Ag, AgCl, Ag/Ag/Cl, Au, etc. (Hermens et al., 1999). The SENIAM guidelines recommends the use of pre-gelled Ag/AgCl electrodes (Hermens et al., 1999), and it was the choice of the present study.

Sensor location is defined as the position of the center of 2 bipolar electrodes on the muscle. Factors which influence the recording of a good and stable sEMG are: the presence of motor points and/or muscle tendons and the presence of other muscles near the SEMG sensor (cross-talk) (Hermens et al., 1999). The cross-talk is also influenced by the inter electrode distance (De Luca et al., 2012). A great variety of methodologies were found: 20 mm for electrodes spacing (Reed et al., 2013b, Wattanaprakornkul et al., 2011, Rajaratnam et al., 2013, Seitz and Uhl, 2012b, Worsley et al., 2013, Larsen et al., 2013, Moraes et al., 2008) and 10 mm for electrode spacing (Szucs and Borstad, 2013, Wickham et al., 2010) and the present choice was 20 mm for electrodes spacing, which are the SENIAM recommendations (Hermens et al., 1999).

Skin preparation is another aspect in which there was poor agreement. The procedures varied with some using a cleaning process that involved only alcohol swabs (Rajaratnam et al., 2013, Szucs and Borstad, 2013), whilst others used alcohol and an abrasive gel to reduce skin impedance (Wattanaprakornkul et al., 2011) or shaving plus alcohol swabs (Moraes et al., 2008). The last procedure involved shaving the area and the use of sandpaper for abrasion to improve adhesion of the electrodes (Seitz and Uhl, 2012b). More importantly, the majority did not detail any skin preparation process (O'Connell et al., 2006, Reed et al., 2013b, Wickham et al., 2010, Worsley et al., 2013, Larsen et al., 2013).

SENIAM recommendations (Hermens et al., 1999) for skin preparation include (1) to shave the skin surface if it is covered with hair, (2) to clean the skin with alcohol and allow the alcohol to vaporize, what is in accordance to the guidelines proposed by Hewson et al. (2003) and (Roy et al., 2007). In the present study the skin was prepared in agreement to the above explained protocols. Disposable razors were used to remove hair, if necessary, tape to remove dead skin, alcohol to degrease and clean the skin, allowing the alcohol to vaporize so that the skin was dry before the electrodes placement. Consequently, skin impedance was kept below 10kΩ, according to Fraser et al. (2013), by careful preparation of the skin.

Onset criteria decision did not seem to be a matter of agreement, with studies using one standard deviation (Rajaratnam et al., 2013), others using 1.5 (O'Connell et al., 2006), 2 standard deviations (Wattanaprakornkul et al., 2011, Szucs and Borstad, 2013, Moraes et al., 2008) and even 3 above the baseline mean (Reed et al., 2013b). Others opted for visual inspection (Wickham et al., 2010, Worsley et al., 2013, Larsen et al., 2013) instead of a math criteria or a threshold based on a percentage of maximum voluntary isometric contraction (Seitz and Uhl, 2012b).

It is important to identify a valid and reliable onset procedure, ensuring that the signal is uncontaminated by noise or signals from adjacent muscles. Irrespective of the procedure adopted, it is highly recommended that the EMG onset obtained using the chosen algorithm is compared with that obtained using visual inspection, before conducting extensive analysis (Kamen and Gabriel, 2010).

The choice of the percentage of maximum voluntary method might be a subject of criticism as explained in the previous section. On the considerations for the choice between 1, 2 or 3 standard deviations above the rest mean, it is proposed that the two standard deviation method seems to be the mathematical criteria that, besides relying on the confidence interval normality rule, it’s also a sensible value to avoid deleterious cleaning of the real onset timing. A preliminary study was carried out to inform the study protocol.

Most of the studies also used a filter, however few showed any agreement on the chosen cut off frequencies and all fail to justify the chosen frequencies or the type of filter used. The literature on shoulder onset timing has referred the use of low pass filters alone (O'Connell et al., 2006, Wickham et al., 2010), low and high pass filters combined (Wattanaprakornkul et al., 2011, Reed et al., 2013b, Seitz and Uhl, 2012b, Worsley et al., 2013) and bandwidth filters (Rajaratnam et al., 2013, Szucs and Borstad, 2013, Larsen et al., 2013). Moraes et al. (2008), did not detail the choice on the filter. Despite the apparent filter use generalization, there is no consensus in the literature in the choice of the filter for shoulder onset timing research, and it should be kept in mind that the filter might not only clean the unwanted noise, but the actual muscle onset, namely in functional movements with progressive, low levels of activation. Because of this fact, a preliminary study was carried out to decide on the option to use or to discharge the filter.

Within the present review, there seems to be some agreement on the fact that some muscles are eligible for sEMG evaluation, whilst others required a fine wire intramuscular electrode to avoid cross-talk. Intramuscular electrodes were mainly used on supraspinatus and infraspinatus muscles, however the literature also suggest the option of analyzing them under the assumption of non-specific placement (Criswell, 2011). Under the above assumptions and the extensive research in the literature the present choice of evaluated muscles are described on appendix 6.

The sample was composed of 21 participants and the correspondent effect size, for repeated measures, within factors ANOVA test, with a priori analysis, was 0.3. According to Cohen (1988), 0,3 is referred as a small effect size and enables us to detect small differences between repetitions.

Although it has been suggested that subcutaneous fat serves as a low-pass filter of the sEMG (Petrofsky, 2008), Cooper et al. (2014), found that a relationship was only present between skinfold thickness and the amplitude of the EMG signals during the non-voluntary muscle actions. Thus is beyond the scope of the present study, therefore anthropometric characteristics weren't considered for these series of studies.

Two small scale studies were performed prior the establishment of the final protocol (study I. A and I. B) and a main study (study II) was carried out to establish the reliability of the measurements on two settings, shoulder abduction in the scapular plane and a volleyball task of hitting a ball.

6.3.5 STUDY I – STUDIES TO ESTABLISH THE METHODS FOR THE FINAL STUDY

6.3.5.1 STUDY I. A. – TO TEST FACE VALIDITY

Aim: To measure face validity of the equipment.

Participant: One male participant aged 30, with no history of neuromusculoskeletal alterations volunteered to take part in this small study.

Material: or Equipment: The bioPLUXresearch; 1 free weight of 10kg; disposable pregelled Al/AgCl bipolar surface electrodes; razor; alcohol; gauze.

Protocol: The right tibialis anterior muscle of the subject was prepared unilaterally (dominant, right side) for sEMG measurements. The skin was shaved and rubbed with alcohol to reduce impedance and the electrode (disposable pre-gelled Al/AgCl bipolar surface electrodes) placed with a center to center distance of 20 mm.

The longitudinal axes of the electrodes were in line with the presumed direction of the underlying muscle fibres. The participant was then asked to lift the weight 11 times. After extracting the data, mean amplitudes values (MAV) were calculated for the rest period and this value was subtracted from the data, this way only information consistent with muscle contraction was included (Figure 5). The representation of 11 contractions in the electromyogram may be indicative of face validity.

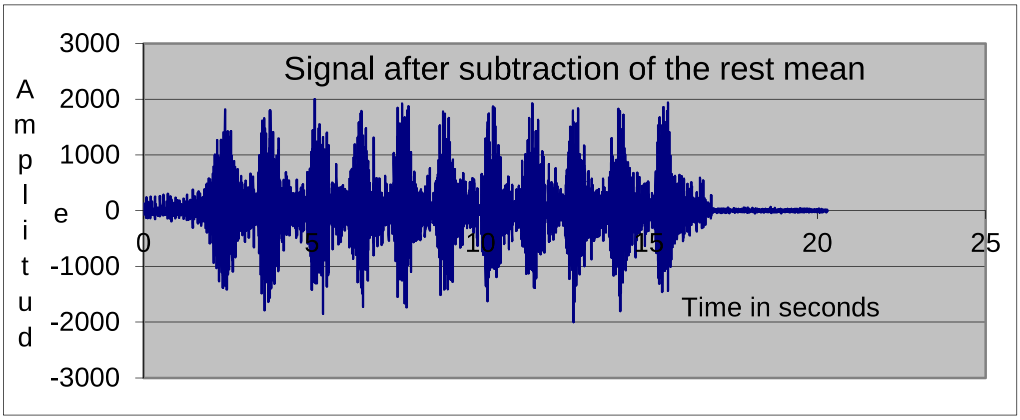


Figure 5. sEMG recording from the right anterior tibialis muscle, representing 11 movements performed by one subject, indicating face validity.

6.3.5.2 STUDY I. B. – ONSET IDENTIFICATION PROTOCOL

Aim: To establish a reliable protocol to measure EMG onset.

Participant: two participants (mean age 25 years old), one male and one female, with no history of neuromusculoskeletal disorder volunteered to take part in this small study.

Material: The bioPLUXresearch; disposable pre-gelled Al/AgCl bipolar surface electrodes; razors; alcohol; gauze.

Procedure:

The anterior deltoid muscle was identified in two participants to which an EMG transducer was attached (Appendix 5 – Electrodes placement for each muscle). Each subject was asked to perform two different tasks one in abduction in the plane of the scapula and the other during a volleyball strike and this procedure was repeated on 3 different occasions to test for repeatability. The tasks used were the same tasks used on the main final study. For a more exhaustive description please see study II chapter (6.3.6.3 Experimental Procedure).

Data Analysis

Figure 6, Figure 8 and Figure 10 represents the first, second and third trials of one subject, in the abduction task, under various conditions of data processing. The same description as for Figure 6 is applied to Figure 8 and Figure 10.

Figure 6.1 is the reference, the raw data to be analyzed. Figure 6.2 represents the data after the constant have been removed from the data (detrend) and the data was then converted into voltage (the signal, in mV = the signal*5000/4096). The first onset was determined by the operator visual inspection. Figure 6.3 represents the data, full wave rectified, with the same processing as in 6.2, but the figure only shows the points 2 standard deviations (SD) above the mean of the noise. For this, first the signal was full wave rectified, then the operator determined the beginning and end of the rest period and a mean for this time window was calculated. Figure 6.3 shows only the signal that was 2 SD above the previous calculated mean. The operator then identified the onset by visual inspection, basing the choice only on the signal above the threshold of 2 SD.

Figure 6.4 represents the same data as in 6.3, but with a specification of time consistency above the threshold of ‘x’ ms. In the figure 6.4 the 5ms criteria was chosen. The onset was identified not by the operator visual inspection, but for the consistency of the ‘x’ ms above the threshold. The program identified the first data point that met the criterion of ‘x’ ms above the threshold of 2 SD above the rest mean. The ‘x’ took values of 3, 4, 5 and 6 ms and for each, the onset was identified.

Figure 6.5 represents the signal (6.2) after a filter was applied. In this case a low pass Butterworth filter, 9th order, was applied with a cut-off frequency of 350Hz. The 350Hz was chosen based on the spectral frequency analysis (Figure 7). No data extraction at this point.

Figure 6.6 represents the signal after a filter (the same as 6.5) was applied, with the same math criteria for determination of onset used on 6.4. Here, the ‘x’ took the same values as 6.4 (3, 4, 5 and 6 ms) and for each, the onset was identified.

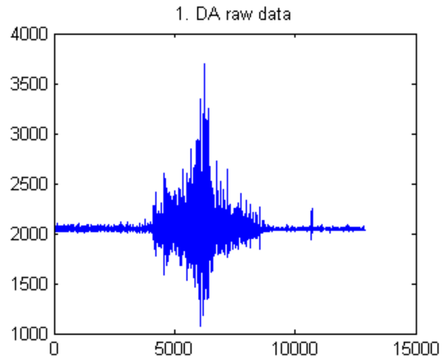


Figure 6.1 Deltoid Anterior muscle onset, 1st trial, sEMG raw data (the reference).

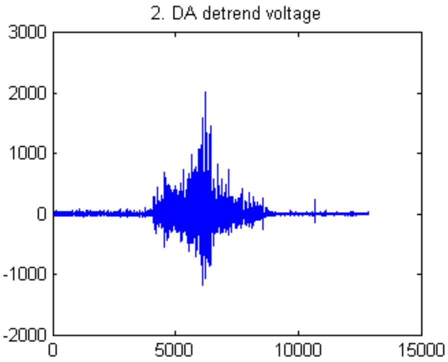


Figure 6.2. EMG data after detrend and voltage conversion (in mV), onset determined by visual inspection.

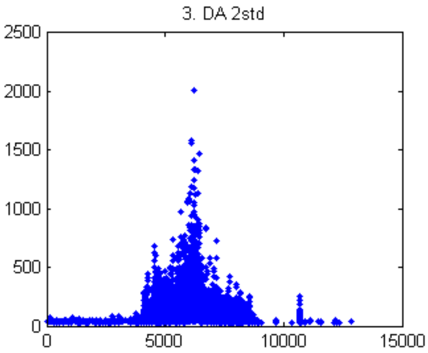


Figure 6.3. EMG data after detrend, voltage conversion, full wave rectification and algorithm applied to show only data 2 SD above rest mean. Onset determined with algorithm and visual inspection of the data.

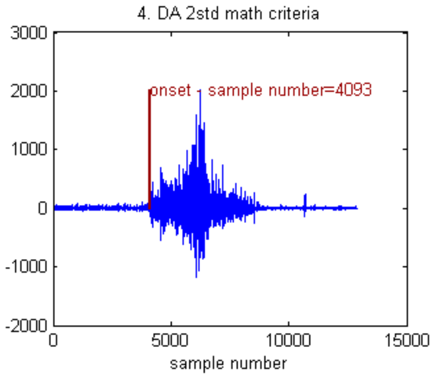


Figure 6.4. EMG data after detrend, voltage conversion, full wave rectification, 2SD above rest mean procedure. The onset criteria was determined with an algorithm that apply a time consistency above threshold.

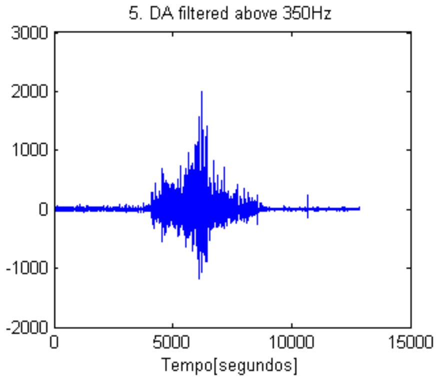
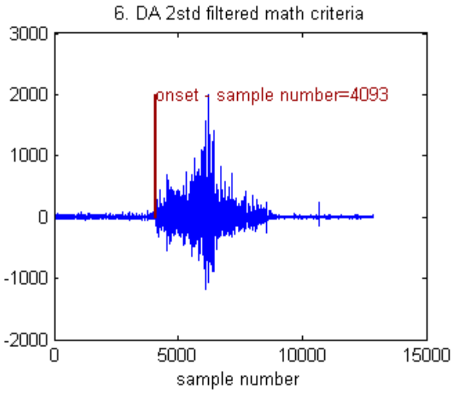


Figure 6.5. The same data as in 6.2, after a low pass butterworth filter, 9th order, with a cut-off frequency of 350HZ.



6.6. The same procedure as in 6.4 plus a low pass butterworth filter.

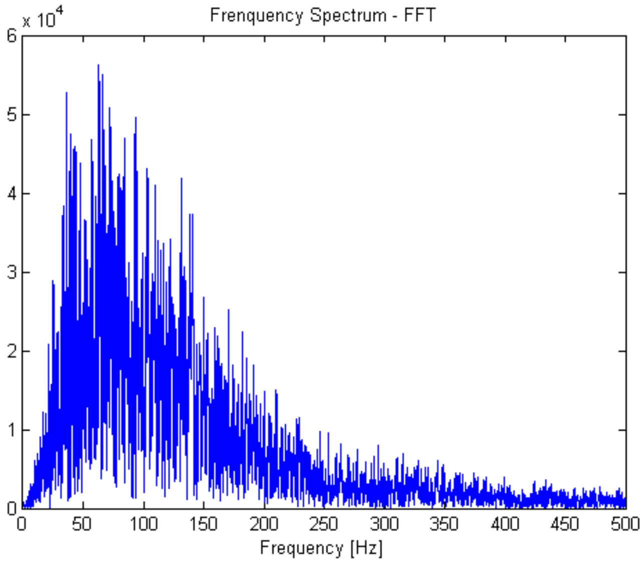


Figure 7. Deltoid Anterior frequency spectrum of the 1st trial. Fast Fourier Transformation procedure.

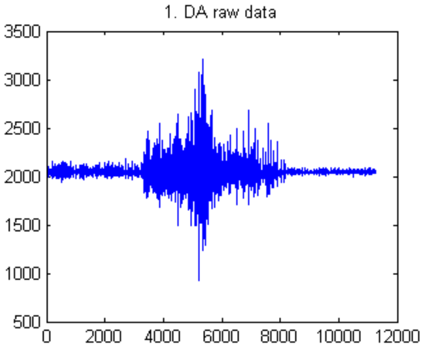


Figure 8.1 Deltoid anterior muscle onset, 2nd trial, sEMG raw data (the reference).

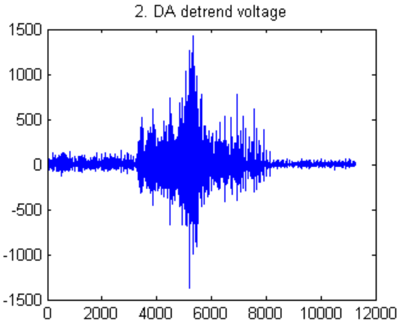


Figure 8.2. EMG data after detrend and voltage conversion (in mv), onset determined by visual inspection.

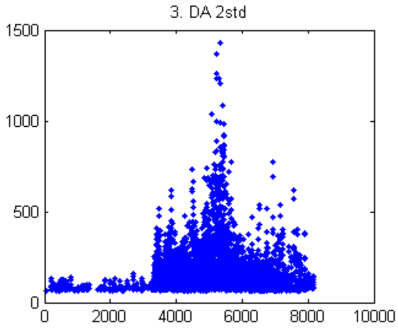


Figure 8.3. EMG data after detrend, voltage conversion, full wave rectification and algorithm applied to show only data 2 SD above rest mean. Onset determined with algorithm and visual inspection of the data;

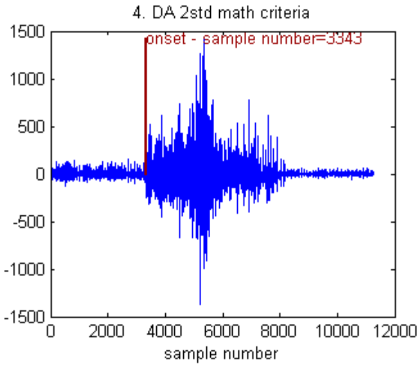


Figure 8.4. EMG data after detrend, voltage conversion, full wave rectification, 2SD above rest mean procedure. The onset criteria was determined with an algorithm that apply a time consistency above threshold.

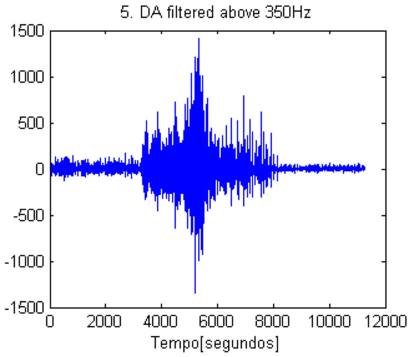


Figure 8.5. The same data as in 8.2, after a low pass butterworth filter, 9th order, with a cut-off frequency of 350HZ.

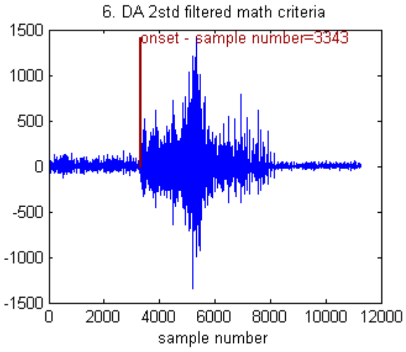


Figure 8.6. The same procedure as in 8.4 plus a low pass butterworth filter.

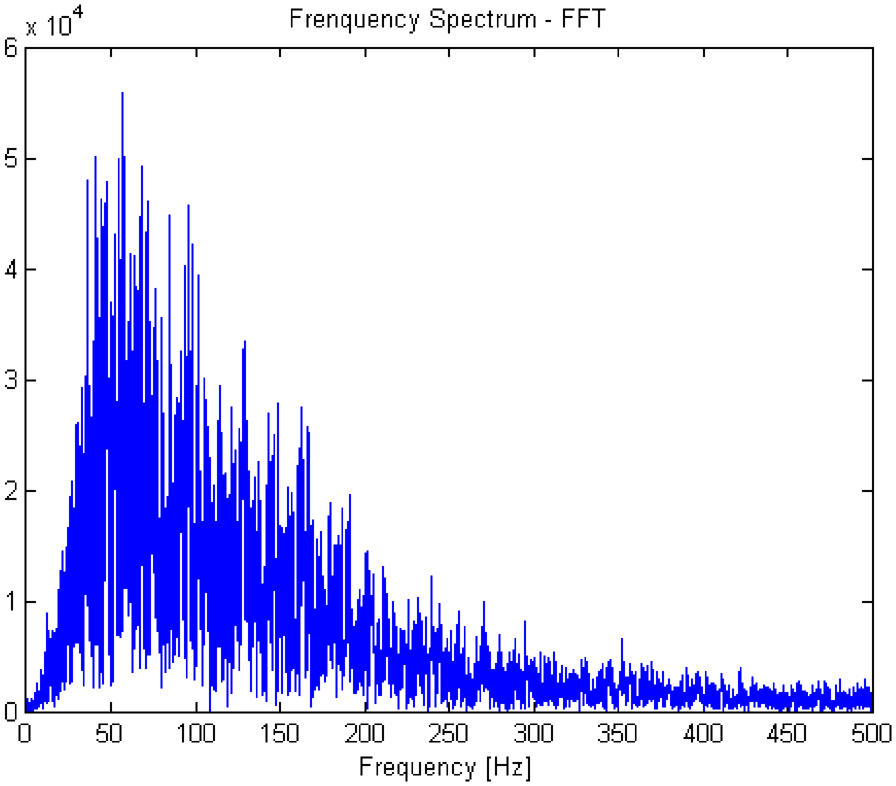


Figure 9. Deltoid anterior frequency spectrum of the 2nd trial. fast Fourier transformation procedure.

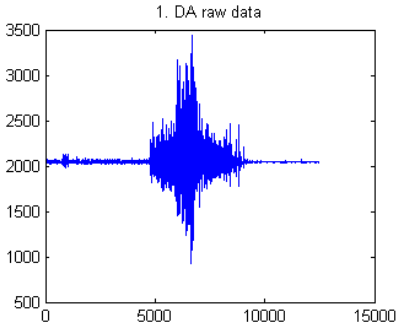


Figure 10.1. Deltoid anterior muscle onset, 3rd trial, sEMG raw data (the reference).

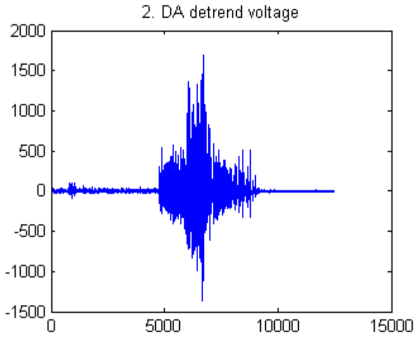


Figure 10.2. EMG data after detrend and voltage conversion (in mv), onset determined by visual inspection.

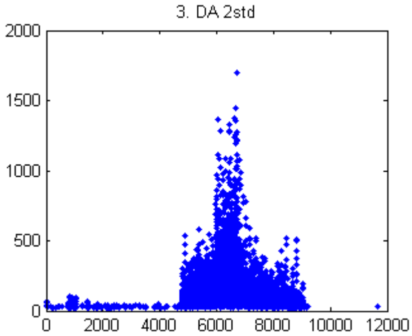


Figure 10.3. EMG data after detrend, voltage conversion, full wave rectification and algorithm applied to show only data 2 SD above rest mean. onset determined with algorithm and visual inspection of the data.

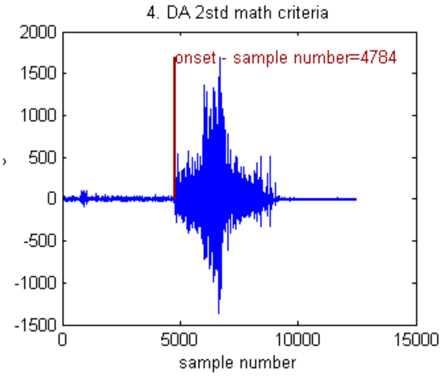


Figure 10.4. EMG data after detrend, voltage conversion, full wave rectification, 2sd above rest mean procedure. the onset criteria was determined with an algorithm that apply a time consistency above threshold.

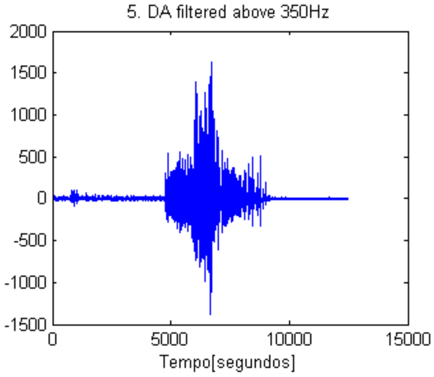


Figure 10.5. the same data as in 10.2, after a low pass butterworth filter, 9th order, with a cut-off frequency of 350hz.

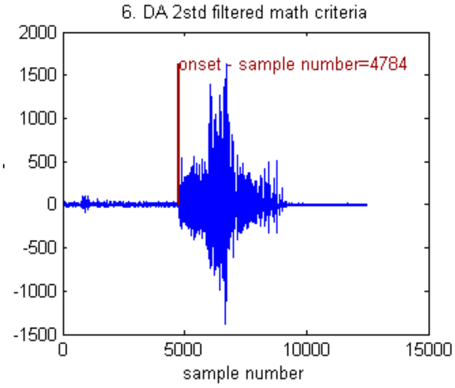


Figure 10.6. the same procedure as in 10.4 plus a low pass butterworth filter.

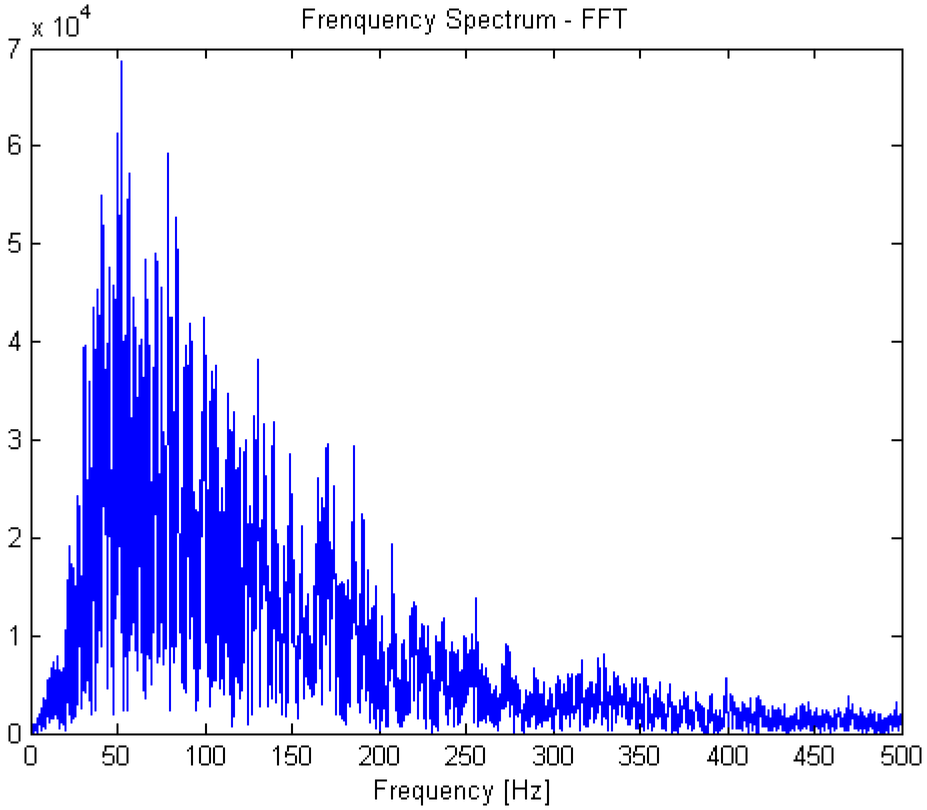


Figure 11. Deltoid anterior frequency spectrum of the 3rd trial. fast Fourier transformation procedure.

The deltoid anterior (DA) onset from each of the 3 trials from the abduction in the scapular plane and the volleyball strike movement were then identified and written down for each of the above mentioned processing methods and each of the participants (Table 13).

For the first (eye ball), the second (2SD), the third ('x' ms above threshold stability) and the forth ('x' ms stability after filtering) methods the 4 possible onsets were identified and written down as components of method's precision.

Table 13. Comparison of 4 methods of deltoid anterior onset determination, for each of the 3 trials on two different tasks (abduction on the scapular plane and volleyball strike). All the data are from the right upper limb, deltoid anterior muscle, presented in milliseconds.

Trial	Detrend/Voltage						2std						2std Math Criteria						2std Math Criteria with Filter					
N=2	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	3ms	4ms	5ms	6ms	Mean	SD	3ms	4ms	5ms	6ms	Mean	SD
Abduction on the scapular plane																								
First participant																								
1	4063	4070	4085	4088	4076.5	11.96	4086	4088	4094	4095	4090.75	4.43	4093	4093	4093	4093	4093.00	0	4093	4093	4093	4093	4093.00	0
2	3265	3333	3342	3345	3321.25	37.85	3267	3337	3343	3344	3322.75	37.30	3267	3267	3343	3343	3305.00	43.89	3267	3267	3343	3343	3305.00	43.88
3	4742	4747	4776	4783	4762.00	20.51	4749	4769	4777	4782	4769.25	14.52	4749	4749	4784	4784	4766.50	20.21	4749	4749	4784	4784	4766.50	20.21
Second participant																								
1	7899	7926	7942	8006	7943.25	45.44	7927	7998	8007	8079	8002.75	62.16	7943	7943	7943	7943	7943.00	0	7943	7943	7943	7943	7943.00	0
2	8077	8125	8133	8149	8121.00	30.98	8085	8126	8133	8229	8143.25	60.96	8078	8078	8078	8078	8078.00	0	8078	8078	8078	8078	8078.00	0
3	4511	4551	4567	4591	4555.00	33.63	4550	4558	4518	4583	4552.25	26.81	4511	4511	4511	4511	4511.00	0	4512	4512	4512	4512	4512.00	0
Voleybal strike																								
First participant																								
1	3549	3563	3576	3587	3568.75	16.42	3459	3528	3551	3563	3525.25	46.49	3550	3550	3550	3550	3550.00	0	3550	3550	3550	3550	3550.00	0
2	2026	2042	2051	2052	2042.75	12.04	2030	2045	2052	2053	2045.00	10.62	2030	2061	2061	2061	2053.25	15.50	2043	2061	2061	2061	2056.50	9.00
3	1580	1608	1639	1684	1627.75	44.58	1579	1613	1641	1686	1629.75	45.27	1581	1581	1581	1610	1588.25	14.50	1581	1581	1581	1608	1587.75	13.50
Second participant																								
1	2235	2261	2285	2309	2272.50	31.77	2277	2309	2325	2337	2312.00	26.00	2309	2309	2309	2309	2309.00	0	2349	2349	2349	2349	2349.00	0
2	1938	1954	1978	2001	1967.75	27.60	2002	2026	2041	2057	2031.50	23.39	2330	2330	2330	2330	2330.00	0	2330	2330	2330	2330	2330.00	0
3	4406	4438	4446	4470	4440.00	26.43	4407	4447	4478	4502	4458.50	41.06	4407	4407	4407	4407	4407.00	0	4407	4407	4407	4407	4407.00	0

The data were tested for normal distribution using the Shapiro-Wilks test and the homogeneity of variances (see appendix 7, table 7, 8, 9 and 10). The data were found to be normally distributed. A Repeated Measures ANOVA was performed to identify (1) possible differences between the 4 methods and there were no significant main effect for methods: $F(3)=0.337$; $p=0.588$, with Greenhouse-Geisser correction, because sphericity was not assumed $p=0.000$. Since no differences were found between methods, the 2STD mathematical method was chosen because of the practicality of the method. The filtering will be avoided, as discussed on section 5.3.4. (2) Possible differences between stabilities above threshold (3, 4, 5 or 6 ms) were studied and there was no significant main effect: $F(3)=2.877$; $p=0.105$, with Greenhouse-Geisser correction, because sphericity was not assumed $p=0.001$. The 5ms threshold was the choice because of stable comparison to visual inspection.

The onset protocol for the main study will be as follows, raw data evaluation for beginning and ending of rest period identification and for beginning and ending of contraction. The point of onset was identified using a mathematical criteria of 2 SD above the mean and 5ms of stability above the threshold. After the mathematical value was displayed the investigator compared the result to the raw data to prevent false onset identification.

The reference for muscle synchronization was the onset of the accelerometer data. The accelerometer axis Z was the reference for the abduction/adduction on the scapular plane and the first of the three axis (X, Y and Z) to detect movement was the reference for the ball exercise. The same method as above mentioned was used for accelerometer onset identification. This way, the accelerometer onset represents the zero or the reference. All pre-activation will be identified as negative and all the post-activation will be identified as positive.

After study A and B, the final study was conducted to assure reliability of the testing procedures and equipment and to establish normal patterns of shoulder motor control.

6.3.6 STUDY II – METHODS FOR THE EMG STUDY

6.3.6.1 PARTICIPANTS

Fourteen healthy right-handed participants, between the ages of 18 and 30 years (mean age of 26.5; 4.07 SD; 7 female and 7 males) were invited to take part in the study. All participants were students of University Fernando Pessoa and were recruited by direct contact. All participants who volunteered were included. The participant information sheet (translated version) was handed out to the willing participants for them to consider prior to commencement of the study.

Exclusion criteria included: calcification or fracture; shoulder instability (positive sulcus and relocalisation tests); previous shoulder surgery; shoulder pain during neck movement, shoulder capsulitis and neurologic disorders. People with generalized ligamentous laxity were excluded from study: positive thumb-forearm sign, recurvatum of either elbow (without previous injury to elbow), or hyperextension of metacarpophalangeal joints, as explained earlier for the IKD studies. Pregnant ladies were also excluded from study.

The exclusion criteria were identified by screening tests and questions performed by the researcher at the time of the first evaluation.

6.3.6.2 MATERIALS

A digital caliper was used to measure the distance between electrodes to assure the accuracy of 20 mm between centers.

A Metronome was set to a constant rhythm (3 seconds) that guided participants through the concentric and eccentric phase of shoulder elevation on the scapular plane. The metronome also assured the same amount of time needed to complete the task, maintaining it constant between participants.

A metal bar was used to maintain the same shoulder height between participants. The chair was adjusted in order for the shoulder to touch the tip of the bar.

The IKD machine was adjusted on the position of the chair, so every participant shoulder was at exactly the same point at start.

A laser pointer was used so the participant could follow a black tape from the floor to the ceiling and the black tape was positioned so the 40º of the scapular plane was kept constant trough the movement, assuring each trial was performed under repeatable conditions.

The electromyographic bio-signal was measured using a bipolar sEMG sensor. sEMG Bioplux Research and a triaxial accelerometer (ACC), xyzPLUX (bioPLUX Research Manual, 2010) were also used.

The characteristics of the bioPLUXresearch (according to equipment manual, Plux, 2010) are: 12 bit channels, with a sample frequency of 1000Hz, CMRR of 110 dB and bipolar configuration (see appendix 5 for further description).

For the second task, a volleyball ball was attached to the ceiling using a rope and a net.

6.3.6.3 EXPERIMENTAL PROCEDURE

Shoulder muscular activity was studied during several functional activities, as described in task 1 and 2.

The dominant upper limb was prepared for evaluation. The skin preparation included disposable razors to remove hair, alcohol to degrease and tape to remove dead skin. After shaving the patient, if the skin surface at which the electrodes have to be placed was covered with hair, tape was used to remove dead skin and gauze soaked with alcohol, in a 10 strokes movement, was used clean the skin, then some minutes were given to allow the alcohol to vaporize so that the skin were dry before the electrodes were placed.

Bipolar sEMG electrodes was used to record the muscular activity of the rotator cuff muscles, anterior, middle and posterior deltoid, long head of biceps, pectoralis major, dorsal anchor, teres major, serratus anterior and finally upper and lower trapezius, during abduction on the scapular plane and during a reproduction of a volleyball technical gesture.

The electrodes were placed using the following procedure: each muscle was palpated and identified, by asking the participant to perform the primary movement of the muscle, isometrically. The electrodes were placed longitudinally on the muscle belly, parallel to the direction of the muscle fibres. The distance between the active electrodes was kept standardized to 20 mm from center to center. The reference electrode was positioned on the olecranon process of the elbow.

Muscles placement was performed according to Criswell (2011) (Appendix 5 – Electrodes placement for each muscle).

To assure low levels of movement artifact, the electrode cables were secured using adhesive tape (Billaut and Bishop, 2012).

Since the elastoplast attachment of the sEMG to the skin can cause a mild allergic reaction. Participants were told to inform the researcher if this occurred in order that the trial could be stopped.

In order to mimic functional movements of the upper limb, the protocol movements were kept as unconstrained as possible:

TASK 1. – ABDUCTION ON THE SCAPULAR PLANE

The scapular plane was determined using a trigonometric math calculation. The seat and target was positioned in a way that the movement was performed at approximately 40º anterior to the coronal plane.

The motor strategies were evaluated while following a black tape with the laser pointer. The participants were seated with their knees and hips at 90º, their feet flat on the floor and their lumbar spine supported. The shoulder girdle was constrained by the belts from the IKD machine. The task started with the upper limb in a neutral position at the side of the body and the tip of the second finger in contact with the laser switch surface. The target (black tape on the wall) was located in an oblique plane (scapular plane).

The metronome was used to ensure a constant rhythm (3 seconds for abduction and 3 seconds for adduction on the scapular plane) was maintained. This was to assure the same duration of adduction and abduction, and the same overall time for every participant (Figure 12).

Figure 12. Abduction in the Scapular Plane, EMG Measurement Apparatus.

The participants were instructed to perform the movement at least twice prior to assessment for familiarization.

TASK 2. – TO HIT A VOLLEYBALL BALL

For the evaluation of a volleyball technical gesture, the motor strategies were evaluated while hitting a volleyball ball - service. The participants were positioned standing and were instructed to hit the ball that was hanging from the ceiling, at the exact height of the participant. They were instructed to step back from the ball (200 mm), to draw the arm back and to hit the ball with the palm of their dominant hand, in a downward movement, with maximum effort (Figure 13).

Figure 13. volleyball technical gesture, emg measurement apparatus.

5.3.6.4 DATA ANALYSIS

The EMG signal was rectified and processed using MATLAB 7.11 (v.2010).

The onset timing identification was performed using the previously explained protocol (study I. B).

The Statistical Package for the Social Sciences SPSS (Inc, Chicago, IL, v 20.0) was used to perform all statistical analyses. A priori level of significance was set at $p \leq 0.05$ for all comparisons.

The data was tested for distribution using the Shapiro-Wilk test and found not to be normally distributed (Appendix 6 – Normality Tests). Non-parametric tests were employed (Pestana and Gageiro, 2005). The Wilcoxon signed-rank test, a non-parametric statistical hypothesis test, was used when comparing two related samples, matched samples and the Friedman’s test, Similar to the parametric repeated measures ANOVA, it is used to detect differences in treatments across multiple test attempts.

The coefficient of repeatability were calculated from the Bland and Altman formula (Bland and Altman, 1996a).The repeatability coefficient shows the limit which it is expected the differences between two measurements to lie.

All variables in the study were described and the mean scores for each trial were used to calculate the intratester test-retest reliability with a one-way random-model intraclass correlation coefficient (ICC). Confidence intervals (CIs) were calculated at the 95% confidence level for the reliability coefficients. Confidence intervals or bounds allow for the expression of a level of certainty of point estimates. To interpret ICC values it was used the benchmarks suggested by Fleis and Shrout (>0.75 excellent reliability, 0.4-0.75 fair to good reliability and <0.4 poor reliability) (Fleiss et al., 2003).

TASK I – ABDUCTION ON THE SCAPULAR PLANE

A. Normal patterns of shoulder motor control

Objective: Establish normal patterns of shoulder motor control

The following table (Table 14) shows the onset timing responses of the muscles around the joint for the abduction movement, in the shoulder of a population of people with no pathology. The accelerometer was used as a reference to determine the beginning of movement and time was registered as baseline against which muscle onset timing was measured. Data was found not to be normally distributed and analyzed using non-parametric statistics.

Table 14. sEMG Onset median and interquartile range (milliseconds) for each muscle during the movement of abduction on the scapular plane, *n*=14.

Muscles	Median	Lower Quartile	Upper Quartile	Min	Max
Biceps	11.00	-16.50	60.50	-107.33	354.00
Deltoid Anterior	-31.84	-46.67	-3.50	-137.33	15.00
Middle Deltoid	-34.84	-51.50	-15.59	-71.33	56.00
Deltoid Posterior	-20.84	-34.00	15.83	51.00	196.33
Latissimus Dorsi	19.00	-23.33	130.92	-76.00	211.00
Infraspinatus	-3.50	-43.34	31.00	-125.33	129.67
Lower Trapezius	42.00	2.42	132.67	-21.00	292.00

Pectoralis, Clavicular portion	114.00	36.42	286.00	-35.33	611.67
Pectoralis, Sternal portion	42.50	17.84	113.17	-63.33	255.3
Teres Major	52.67	19.00	84.42	-9.00	199.33
Serratus	-1.00	-32.84	37.00	-109.3	114.67
Supraspinatus	-15.33	-60.67	22.75	-113.67	62.33
Upper Trapezius	26.67	-11.75	84.08	-81.67	434.67

Legend: negative values indicate activation before the movement started

During the movement of abduction in the scapular plane, generally the participants pre-activated the following muscles (in order): middle deltoid, anterior deltoid, posterior deltoid, supraspinatus, infraspinatus and serratus anterior.

The supraspinatus location is referred as a non-specific placement for sEMG because of the Upper trapezius cross-talk. Due to this issue, upper trapezius onset was compared to supraspinatus onsets. Since the supraspinatus and upper trapezius onsets are not normally distributed a related-samples Wilcoxon test was performed and there were significant statistical differences (Z= 723.50, p=0.001) between the onsets, suggesting an independent origin of muscular activity.

The following boxplot graphs (Figure 14) display the median and interquartile range for each evaluated muscle.

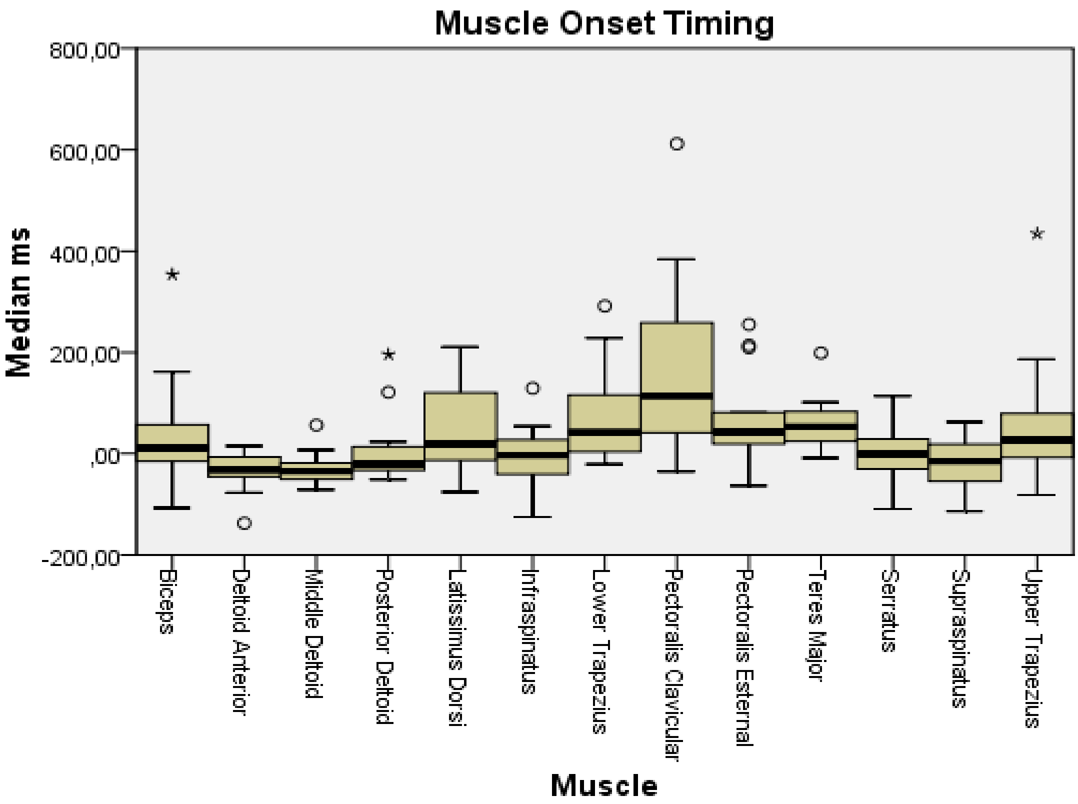


Figure 14. Onset timing median and interquartile range for each evaluated muscle during the movement of abduction in the scapular plane.

B. Reliability of measures of shoulder motor control

Objective: To assess reliability of muscle onset timing measurements of the muscles around the shoulder joint.

Table 15 shows the onset timing produced in each trial (during the movement of abduction in the scapular plane) in the shoulder of a population of people with no pathology.

Table 15. sEMG Onset median and interquartile range (lower quartile, LQ, and upper quartile, UQ, in ms) for each muscle during the movement of abduction on the scapular plane. The Friedman's two –way analysis of variances by ranks for repeated measures were also calculated.

Muscle	Trial 1			Trial 2			Trial 3				
	Median	LQ	UQ	Median	LQ	UQ	Median	LQ	UQ	$\chi^2(2)$	*p*
Biceps	54.00	-4.25	129.00	-10.50	-53.00	44.75	19.00	-21.00	82.00	4.429	0.109
Deltoid Anterior	-31.50	-60.00	-2.75	-34.00	-86.25	0.75	-27.00	-54.50	0.50	0.982	0.612
Middle Deltoid	-23.50	-51.00	6.50	-40.00	-69.50	-5.00	-14.50	-60.00	-3.50	0.333	0.846
Deltoid Posterior	-31.00	-51.00	59.50	-1.00	-56.75	45.50	-14.00	-51.00	24.00	1.857	0.395
Latissimus Dorsi	13.50	-37.50	94.25	0.00	-46.50	84.00	52.50	-26.25	103.00	1.857	0.395
Infraspinatus	7.50	-76.00	53.50	13.50	-68.25	50.75	8.50	-31.50	29.75	0.327	0.849
Lower Trapezius	23.50	-3.50	131.50	47.00	12.75	108.50	21.00	-6.75	156.50	0.571	0.751
Pectoralis, Clavicular	191.50	19.50	333.75	66.00	19.00	427.25	104.50	-1.50	185.00	6.143	0.046*
Pectoralis, Sternal	33.00	11.75	159.00	36.00	0.25	84.75	52.50	-18.00	113.00	0.000	1.000
Teres Major	112.00	-3.75	155.00	50.50	-42.25	96.50	60.10	6.75	81.50	1.000	0.607
Serratus Anterior	-3.00	-28.50	84.25	-11.50	-30.25	17.25	4.00	-47.50	30.75	2.714	0.257
Supraspinatus	6.00	-49.00	58.25	15.00	-63.25	25.00	-26.50	-83.00	2.50	3.000	0.223
Upper Trapezius	40.00	-6.25	116.00	11.00	-83.00	81.25	36.50	5.00	61.25	0.571	0.751

Since not all of the items were normally distributed, non-parametric testing was employed. A Friedman's two-way analysis of variance for related samples was performed and it did not show significant differences between trials, with exception of the clavicular portion of the pectoralis muscle, that were significant, suggesting the three trials are similar for all the muscles but the clavicular portion of the pectoralis muscle.

Table 16 shows the intraclass correlation for each muscle and the related statistics.

Table 16. One-way random intraclass-correlation coefficient, single measures and associated confidence intervals for abduction in the scapular plane.

Muscle	ICC	95% CI Lower Bound	95% CI Upper Bound
Biceps	0.65	0.36	0.85
Deltoid Anterior	0.21	-0.09	0.58
Middle Deltoid	0.05	-0.27	0.33
Deltoid Posterior	0.52	0.43	0.92
Latissimus Dorsi	0.42	0.09	0.73
Infraspinatus	0.14	-0.15	0.52
Lower Trapezius	0.31	-0.01	0.65
Pectoralis, Clavicular	0.79	0.58	0.92
Pectoralis, Sternal	0.38	0.05	0.70
Teres Major	-0.19	-0.36	0.13
Serratus	0.36	0.03	0.69
Supraspinatus	0.12	-0.16	0.50
Upper Trapezius	0.20	-0.10	0.57

The clavicular portion of the pectoralis muscle represented excellent agreement, while the biceps, the posterior portion of deltoid, latissimus dorsi, the sternal portion of pectoralis muscle and serratus demonstrated fair to good agreement. However the intraclass correlation coefficients provide a statistical mean of testing the reliability, care should be taken when interpreting the absolute ICC values, mostly because higher ICC does not necessarily demonstrate less variability, because ICC values can also be affected by various factors as will be discussed later in the discussion chapter.

Moreover, the majority of cases with lower ICC had a very small interquartile range, suggesting the repetitions were very similar and this could explain the low ICC.

C. Variance of shoulder motor control, Study of Repeatability

Objective: To establish the natural variability in muscle onset timing in normal population and study the repeatability.

Bland and Altman coefficient of repeatability were reported in the next table (Table 17).

Table 17. Results of between trials repeatability – Bland and Altman coefficient of repeatability (B&A), in ms.

Muscle	B&A
Biceps	205.53
Deltoid Anterior	142.01
Middle Deltoid	165.69
Deltoid Posterior	162.90
Latissimus Dorsi	261.77
Infraspinatus	241.43
Lower Trapezius	300.97
Pectoralis, Clavicular	217.76
Pectoralis, Sternal	267.96
Teres Major	360.06
Serratus	185.84
Supraspinatus	209.46
Upper Trapezius	462.61

The muscles listed on the previous table had a Bland and Altman coefficient of repeatability ranging from 142.01 (Deltoid Anterior) to 462.61 (Upper Trapezius). Deltoid presents lower level of variance because it is considered to be the prime mover for the movement, namely the anterior and middle portion of deltoid. Upper and lower portions of trapezius muscles and teres major have demonstrated higher level of variance, suggesting more inconsistency in the way non-prime movers have been activated across trials, for the same subject. Moreover, in the case of upper trapezius, any differences between the patients with SIS and the normal will have to be at least half a second different in timing of muscle activation.

A. Normal patterns of shoulder muscles onset timing

Objective: Establish normal patterns of shoulder motor control

The following table (Table 18) shows the onset timing responses for the volleyball task movement, in the shoulder of a population of people with no pathology.

Table 18. sEMG onset median and interquartile range (ms) for each muscle during the volleyball task, *n*=14.

Muscles	Median	Lower Quartile	Upper Quartile	Min	Max
Biceps	31.50	12.50	51.25	-37.67	118.33
Deltoid Anterior	-7.50	-30.58	33.42	-73.00	46.67
Middle Deltoid	-24.67	-53.17	-1.67	-66.00	39.00
Deltoid Posterior	-6.67	-29.42	16.75	-45.33	44.33
Latissimus Dorsi	29.34	15.59	87.92	-2.00	135.33
Infraspinatus	-16.17	-33.58	13.50	-38.33	80.67
Lower Trapezius	-5.84	-15.00	22.50	-39.33	66.00
Pectoralis, Clavicular portion	128.00	86.09	225.67	20.67	749.67
Pectoralis, Sternal portion	101.50	66.83	154.75	18.67	418.00
Teres Major	31.84	-22.25	66.25	-36.33	145.67
Serratus	28.84	-4.08	55.42	-37.00	133.33
Supraspinatus	0.00	-39.42	41.50	-55.00	135.33
Upper Trapezius	33.34	8.33	59.59	-39.67	86.00

During the volleyball task, generally the participants pre-activated the following muscles (in order): middle deltoid, infraspinatus, anterior deltoid, and posterior deltoid, followed by lower trapezius.

Since the supraspinatus and upper trapezius onsets are not normally distributed a related-samples Wilcoxon test was performed. Significant statistical differences (*p*=0.000) between the onsets, were found. This suggests that the data from each muscle is being recorded independently.

The following boxplot graph (Figure 15) displays the median measurement for each evaluated muscle with interquartile range.

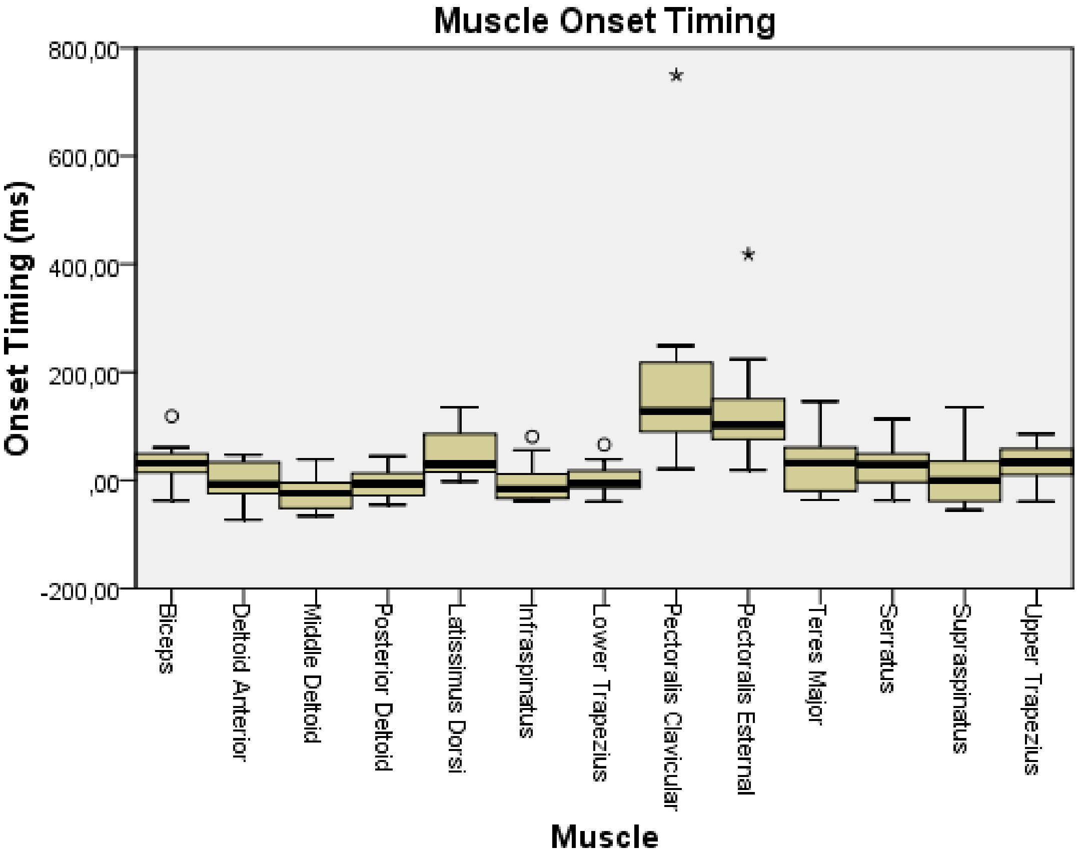


Figure 15. Onset median and interquartile range for each evaluated muscle during the volleyball task.

B. Reliability of measures of shoulder motor control

Objective: To assess reliability of shoulder motor control measurements.

The following table (Table 19) shows the onset timing produced in each trial (during the volleyball task) in the shoulder of a population of people with no pathology.

Table 19. sEMG Onset Median and Interquartile Range (lower quartile, LQ and upper quartile, UQ, ms) for each muscle during the volleyball task, n=14. The Friedman's two –way analysis of variances by ranks for repeated measures were also calculated.

Muscle	Trial 1			Trial 2			Trial 3				
	Median	LQ	UQ	Median	LQ	UQ	Median	LQ	UQ	$\chi^2(2)$	p
Biceps	19.00	-12.25	67.00	8.50	-4.00	70.00	30.50	2.75	76.75	1.00	0.607
Deltoid Anterior	-3.00	-44.25	43.25	-7.50	-18.00	24.75	-10.00	-30.50	22.75	2.29	0.319
Middle Deltoid	-23.00	-84.50	0.75	-14.00	-31.50	18.75	-15.50	-33.00	2.75	1.86	0.395
Deltoid Posterior	-10.00	-33.75	27.75	-14.00	-36.00	9.25	-12.00	-34.25	35.25	0.04	0.982
Latissimus Dorsi	25.00	-3.50	76.75	34.50	-10.75	70.50	61.50	14.50	117.75	2.71	0.257
Infraspinatus	-17.50	-32.00	9.50	-3.00	-36.00	16.75	2.00	-41.50	41.25	1.71	0.424
Lower Trapezius	11.00	-27.50	42.25	1.00	-19.00	16.50	-8.50	-27.00	37.00	0.42	0.424
Pectoralis, Clavicular	164.00	74.25	239.50	89.50	13.75	224.75	121.00	76.50	200.25	3.00	0.223
Pectoralis, Sternal	86.50	43.25	167.75	83.50	1.75	175.25	104.50	58.75	198.00	1.71	0.424
Teres Major	36.50	-11.00	80.75	28.50	-6.00	63.25	3.00	-21.25	62.25	0.14	0.931
Serratus Anterior	35.00	6.75	77.00	13.50	-7.50	46.00	28.50	-18.25	65.50	2.87	0.238
Supraspinatus	7.50	-19.00	75.50	-6.00	-38.00	37.25	-9.00	-31.00	45.75	0.26	0.880
Upper Trapezius	38.00	8.75	90.75	31.50	-3.00	82.25	6.50	-2.00	53.25	1.13	0.569

The data was not normally distributed (for further information please see Appendix 6 – Normality Tests), a Friedman's two-way analysis of variance was performed to verify if the samples from each trial were different. No significant differences between trials for the 3 measured angles were demonstrated.

The following table (Table 20) represents the ICC values for each muscle and lower and upper bound confidence intervals.

Table 20. One –way random Intraclass-correlation coefficient, single measures and associated confidence intervals for a volleyball task.

Muscle	ICC	95% CI Lower Bound	95% CI Upper Bound
Biceps	0.23	-0.78	0.59
Deltoid Anterior	0.35	0.27	0.68
Middle Deltoid	0.12	-0.16	0.51
Deltoid Posterior	0.07	-0.20	0.45
Latissimus Dorsi	0.45	-0.24	0.39
Infraspinatus	0.23	-0.07	0.60
Lower Trapezius	0.04	-0.21	0.43
Pectoralis, Clavicular	0.19	-0.11	0.57
Pectoralis, Sternal	0.20	-0.10	0.57
Teres Major	0.44	0.12	0.74
Serratus Anterior	0.25	-0.06	0.61
Supraspinatus	0.19	-0.11	0.56
Upper Trapezius	0.24	-0.07	0.61

The anterior portion of deltoid, latissimus dorsi and teres major muscles demonstrated fair to good agreement. For the rest of the muscles, however, low ICC was found; in some of the cases the interquartile range was small, what can be associated with low variability. With low variability in the data the ICC value may be lower, and this will be discussed later in this chapter.

C. Variance of muscle onset timing, Study of Repeatability

Objective: To establish the natural variability in muscle onset timing in normal population and study the repeatability.

Bland and Altman coefficient of repeatability were reported in Table 21.

Table 21. Results of between trials repeatability – Bland and Altman coefficient of repeatability (B&A), in ms.

Muscle	B&A
Biceps	125.81
Deltoid Anterior	115.60
Middle Deltoid	134.80
Deltoid Posterior	119.17
Latissimus Dorsi	192.51
Infraspinatus	126.56
Lower Trapezius	126.02
Pectoralis, Clavicular	649.27
Pectoralis, Sternal	369.04
Teres Major	138.15
Serratus Anterior	137.09
Supraspinatus	195.46
Upper Trapezius	124.45

The muscles demonstrated a B&A coefficient of repeatability ranging from 115.60 milliseconds (anterior portion of deltoid muscle) and 649.27 milliseconds (clavicular portion of pectoralis muscle). Deltoid presents lower level of variance because it is considered to be the prime mover for the movement, the same for serratus, infraspinatus, teres major, upper and lower trapezius. The pectoralis muscles have demonstrated higher level of variance, suggesting more inconsistency in the way non-prime movers have been activated across trials, for the same subject. The large coefficient from the pectoralis muscle might be a consequence of their small importance during the measured movement.

6.3.6.6 DISCUSSION

The results suggested that the onset technique using 2 standard deviations above the rest mean, with stability above threshold of 5 milliseconds, was a reliable method for detecting neuromuscular onset. For further information please see section 5.3.5.

The movement of abduction in the scapular plane was performed with pre-activation of the muscles middle, anterior and posterior deltoid, supraspinatus and infraspinatus and serratus muscles (presented in order).

For healthy participants, deltoid muscle has been described as a prime mover for the movement of abduction (Cael, 2012), even for abduction in the scapular plane (Kendall et al., 2005, Szucs and Borstad, 2013, Seitz and Uhl, 2012b, Reed et al., 2015). Although more activated in the coronal plane (Reed et al., 2015) when compared to simple scapular plane or scapular plane plus 30 degrees anterior, middle deltoid has still been considered the prime mover for the abduction movement and the present study corroborates that fact. Moreover, the data from the present study suggest that the anterior and posterior portions of deltoid contribute for stability and precise angle movement during the abduction movement.

Supraspinatus was recruited prior to movement of the humerus, but not earlier than all sections of deltoid, as in the study by Reed et al. (2013b). Therefore, the common statement that supraspinatus initiates abduction is misleading. Furthermore, its similar initial activation time to infraspinatus could also suggest that it may have a functional role as part of the rotator cuff to stabilize the glenohumeral joint during abduction and to, therefore, increase the efficiency of the deltoid in producing abduction torque.

Supraspinatus, along with infraspinatus are thought to stabilize the humeral head in the glenoid fossa, depressing the humerus as prime movers elevate the shoulder (Cael, 2012, Kibler et al., 2014). According to Reed et al. (2013b), to perform elevation in the scapular plane, there is pre-activation of supraspinatus, subscapularis, serratus anterior, lower trapezius, infraspinatus, upper trapezius and middle deltoid. In comparison to this study, they did not evaluate all the muscles considered for this specific movement (for example, they have missed deltoid anterior), and some of their findings are not in agreement with this study. Namely the preactivation of lower and upper trapezius that are directly related to control and stabilization of the scapula during the glenohumeral movement. The results from the present study suggest that although serratus anterior (also related to scapulohumeral rhythm) was pre-activated, both lower and upper sections of trapezius muscle were not, what is suggestive of prioritization of abduction, external rotation and scapular stability during shoulder abduction (serratus anterior), while upper and lower sections of trapezius contributions occur later in the process, perhaps enabling adjustments for progression of the movement.

During the volleyball task, there were pre-activation of (in order) middle deltoid, infraspinatus, anterior deltoid, posterior deltoid, shortly followed by lower trapezius muscle. To date, there are no publications to allow comparison for the volleyball task. The interpretation of the findings suggest that the initiation of the abduction movement is performed by the middle deltoid, much later the posterior and anterior deltoid participates in the same movement, adjusting the position. Closely after the beginning of the elevation, the infraspinatus centers the humeral head in the glenoid fossa, increasing stability and externally rotating the shoulder. Lower trapezius externally rotates the scapula to prevent impingement, adducts and depresses the scapula.

There were no statistical differences between trials suggesting that the samples from all trials had similar characteristics. It is only not true for the clavicular portion of the pectoralis muscle, during the movement of abduction. This could suggest that fewer replications would be needed in future studies, since the variable did not change from one measurement to the next.

The non-specific supraspinatus placement is controversial because of the potential for cross-talk from the upper trapezius. Cross-talk has been defined as electrical activity from adjacent or distinct muscles recorded by the electrodes over the muscle of primary interest (Criswell, 2011). During both the abduction movement and the volleyball task, the analysis of the data suggested the recorded samples from the described sites were different, meaning should be considered the two as individual muscle contributions.

The repeatability coefficient shows the limit which it is expected the differences between two measurements from the same subject to lie (Bland and Altman, 1996a).

The repeatability coefficient ranged from 142.01ms (deltoid anterior) to 462.61ms (upper trapezius), for the abduction movement. These results suggest that, for example in the case of the muscle anterior deltoid, it is 95% confident that any measure of the onset of anterior deltoid in the elevation movement will be accurate to within 14 hundreds of a second. Upper and lower portions of trapezius muscles and teres major have demonstrated higher level of variance, perhaps due to the great variability in the previously described scapular rhythm.

The absence of statistical difference between trials did not support a learning tendency from trial to trial. According to Hwang et al (Hwang et al., 2013), prior experiences may induce anticipated physical responses, which wasn't observed in the present study.

For the volleyball task, the repeatability coefficients ranged from 115.60ms (DA) to 649.27ms (PC). In fact, deltoid muscle (the prime mover for the referred movement), demonstrated lower levels of variance, as did serratus anterior, infraspinatus, teres major, upper and lower trapezius.

ICC values presented fair to good agreement for biceps, deltoid posterior, latissimus dorsi, lower trapezius, the external portion of the pectoralis muscle and serratus, while the clavicular portion of pectoralis muscle showed excellent agreement for the abduction movement. The anterior portion of deltoid and teres major demonstrated fair to good agreement for the volleyball task, all the other non-listed muscles presented lower ICC values. In 2008, Dorel et al. (studied the onset repeatability of lower limb muscles during pedaling, however a lower limb study, their study was the only one that addressed the onset timing repeatability. Although they have found better ICC values, they have only studied 10 participants, and all trained athletes, for that specific task, with consequent adaptation muscle strategies for that specific task, which was not the case of the present study. Although ICC is one of the most used statistical methods for testing the reliability in orthopedic research and has been found to be useful, there could be pitfalls when using the ICC. It has been criticized for not reflecting the clinical implications of measurement error and for being influenced by the variance of the data (Lee et al., 2012). If participants differ little from each other, ICC values will be small even if trial-to-trial variability is small. If participants differ from each other a lot, ICCs can be large even if trial-to-trial variability is large. Thus, the ICC is context specific (Weir, 2005).

Although the prime movers and synergists presented the best repeatability scores, there was some degree of variability in the rest of the muscles, coherent with variability of the motor strategy for an unconstrained functional task. Vasseljen et al. (2012), had similar results in the abdominal muscles. In an open kinematic chain, motion does not occur in a predictable manner because joints may function either independently or in unison (Levangie and Norkin, 2011). It is known from the literature that intra-individual movement consistency and motor invariance, even in elite athletes, is an abstraction since the research did not seem to support the concept (Bartlett et al., 2007). The large variability in muscle recruitment patterns has been observed both within and between normal participants (Bartlett et al., 2007, Vasseljen et al., 2012). Most of all, it is hypothesized that if movements were repeated identically, overuse syndromes due to overload of the tissues, would develop and the injury risk would increase (Bartlett et al., 2007), furthermore in contrast to traditional uniaxial movement analysis, multi-segmental or multi-axial movements, like the ones performed in the glenohumeral joint (an enartrosis), are more prone to variability (Bartlett et al., 2007).

The best repeatability scores were found for the prime movers for abduction in the scapular plane (deltoid anterior, posterior and middle deltoid, serratus and supraspinatus) and this may be a reflection of the smaller variability of muscles which are the principal contributors to the movement.

Limitations

The major limitation of this study lies in the fact that it only takes into account timing variables (onset), without considering the magnitude of the EMG variables. Regarding the usage of EMG, limitations include technical difficulties with EMG equipment and data analysis. Firstly the fact that deep muscles, such as the rotator cuff muscles, can only be measured using the complex testing with intramuscular electrodes, therefore not all muscles could be analyzed. Secondly, some participants expressed more noise to signal ration than other participants, despite the efforts with skin preparation. Furthermore, large standard deviations might be explained by (a) the small number of participants analyzed, (b) muscle activity patterns are individual, and maybe data of individuals should not be combined; or (c) perhaps signal variations due to fat and connective tissue as seen with surface electrodes cause such standard deviations. The prevalence of being overweight or being obese is commonly assessed using body mass index (BMI), a height/weight formula with a strong correlation to body fat content. WHO criteria define overweight as a BMI of at least 25 kg/m^2 and obesity as a BMI of at least 30 kg/m2 and all the participants involved in the study had BMI’s within the normal range. However some criticism exist in the literature about the lack of sensibility of the BMI and future studies should include skinfold measurements.

Crosstalk is another aspect of concern, however efforts have been made to minimize it, namely the choice of pediatric electrodes, with an inter-electrode distance of 20mm. For the cases the crosstalk was inevitable because of the proximity, than statistical analyzes of differences between sites of record were performed, to assure they were distinct contributions, e.g. supraspinatus and upper trapezius.

6.3.6.7 CONCLUSIONS

There were no differences between trials, with the exception to the clavicular portion of the pectoralis muscle during the abduction movement, representing good consistency on the evaluations. There was pre-activation of all sections of the deltoid and infraspinatus muscles, both in the movement of elevation in the scapular plane on the volleyball task and pre-activation of serratus anterior and supraspinatus in the abduction movement. In the volleyball task lower trapezius was also pre-activated. The findings were in line with the literature of shoulder motor control, for the described movement. While relative coefficients of reliability were poor, accuracy and repeatability were good for prime movers. The data suggested that muscle onset timing of muscles that are not agonists or synergists of the desired movement, are more variable. Small changes in timing of muscle onset of the prime movers and synergists can be interpreted as meaningful changes, while for muscles that are not agonists or synergists for the desired movement larger changes in activity pattern would be needed before a significant change could be identified.

CHAPTER VII: DISCUSSION OF PILOT STUDY RESULTS, DIRECTION TO FUTURE STUDIES AND OVERALL CONCLUSIONS

7.1 DISCUSSION OF PILOT STUDY RESULTS

The findings from the position sense studies suggest that, for all the angles that were measured, the healthy participants underestimated the reference angle. This finding is contrary to the work of Anderson and Wee (2011a), who have reported that healthy control subjects generally overestimated the target during scapular plane abduction. However, their measurement protocol involved the use of a motion analysis system and not the IKD. This different methodological approach, in addition to a different movement analyzed (Anderson and Wee (2011a), studied two criterion positions during the movement of abduction in the scapular plane, while the present study investigated rotation at 90º of abduction, in the scapular plane), which may explain the different findings.

Examination of the between trials findings indicated that there were no differences. The implications of these findings were fully discussed in the results chapters. However the ICC value was low with poor to fair reliability. The highest ICC coefficient was found at 80º position, where the variance of the data was also greatest, which may have increased the ICC score as mentioned in previous discussion sections. The repeatability of the measurements ranged between 15º and 18º, and whilst this is a broad range, as indicated earlier, the choice of uncontrolled speed, where the participants did not have to work against a resistance, to better mimic free functional movement, could have been more challenging for the participant, in comparison with previously published data. Some constraint of the movement could be a useful modification to the protocol for future studies. The present study could sacrifice validity to improve reliability, by using a resisted mechanism against which the subject has to exert force as they move, while this might be easier for research purposes, it would not represent a real functional movement. Moreover, one of the limitations of the published literature is to use a preselected speed for movements during testing, which in turn could assist the identification of target angle through counting. Although neither is perfect, it is the aim of the present study to represent free upper limb movement, which would not be possible using constrained and controlled speed setting.

It is known that capsuloligamentar structures and antagonists muscle spindles are more stretched at the end of ROM. This therefore has implications for better proprioceptive awareness (Janwantanakul et al., 2001, Felli et al., 2012). In this study, the participants did not show a tendency for smaller position sense error with increase in angle. This finding corroborates the results presented by Suprak (2011) who suggested that this lack of difference across the range of motion is only true for unconstrained movement. Thus suggesting that the present study might have been able to simulate true unconstrained functional shoulder movement, even within the constrained system of the IKD. These findings also corroborate the possibility that muscle spindles are a dominant source of afferent feedback regarding shoulder joint position sense in unconstrained movements, even approaching end ROM, when the capsuloligamentous receptors are active. Since the inspiration for this project was driven by an interest in the role of altered muscle action in patients with subacromial impingement syndrome it is interesting to note that SIS patients may show different/disrupted mechanisms for proprioceptive awareness. Alterations in proprioceptors could be present by virtue of alterations in the mechanical restraints of the joint, that act as mechanoreceptors, thus contributing to proprioceptive information (Myers et al., 2006).

Anderson and Wee (2011a), reported the absolute difference between participants with SIS and controls to be 4.2±3.1º. The results of the Bland and Altman analysis from the present study indicate that the level of accuracy that can be expected from the data ranges from 14.49º, at 0º to 18.31, at 45º, which is greater than the level quoted by Anderson and Wee (2011). This indicates that the present position sense protocol is insufficiently sensitive to detect differences between the healthy and the pathological groups. This further supports the suggestion that a protocol involving a more constrained velocity may be more useful and worthy of consideration in future studies.

The force reaction protocol indicated that in 4 out of 6 measurement angles/directions, the participants underestimated the reference point and that is in line with previous investigation (Maenhout et al., 2012). It is suggested by Maenhout et al. (2012), that the

SIS patients will overestimate it. However the physiological basis of this mechanism is still not clear. They found that regardless of the direction of the test, that patients overshoot the target when compared to asymptomatic participants; nevertheless, no difference was found between the painful and asymptomatic side in patients. This may be suggestive of a more global response, but that has yet to be established. They also proposed that overestimation of muscle forces, required for a given task, might further aggravate the symptoms and should be taken into account during rehabilitation.

In terms of differences between trials, it was only found for 80º (both directions) and at 0º (external rotation). In all the cases the difference was always between the first trial and the last. Thus in future studies it would be advisable to discard the first trial or analyze it separately.

A further finding was the significant greater error as the arm was moved further from the neutral position, for internal rotators, and the opposite is also true for external rotators. Moreover, the amount of produced errors decreased with an increase in external rotation, which is in line with previously explored literature (Maenhout et al., 2012, Janwantanakul et al., 2001). It is, however, not known whether SIS patients demonstrate greater levels of error as a result of the development of adaptive mechanisms (Haik et al., 2013) to deal with the condition. The topic remains controversial, mostly because perceptual learning; the improvement of sensory discriminative capacity as a result of practice (Janwantanakul et al., 2001), may mediate against the compromised mechanical restraints and compromised sensorimotor system of SIS patients (Myers et al., 2006).

ICC scores suggested excellent reliability and it was found that the best repeatability score was for internal rotation, middle range. External rotation is a movement that is not commonly used during functional movements or activities. Moreover the musculature is weaker when moving into external rotation. These factors could contribute to explaining why the reliability scores were lower for external rotation. Conversely, the movements of internal rotation are more commonly used and therefore may be better coordinated, which in turn may explain the higher reliability scores. In fact, in favor of the debate between nature and nurture, the literature generally reports greater strength ratios for the internal rotators (Riemann et al., 2010) and it is independent of sports practice (Noffal, 2003), suggesting that internal rotators are congenitally stronger and not a result of repeated practiced movement alone. Overall, the force reaction protocol is considered to be accurate and with sufficient rigor that it could be included in future studies.

During the movement of abduction in the scapular plane, there is pre-activation of (by order) middle, anterior and posterior deltoid, supraspinatus, infraspinatus and serratus anterior. Middle deltoid initiates the elevation, almost in synchrony with both anterior and posterior aspects of the muscle. Supraspinatus and infraspinatus seem to stabilize and center the humeral head as the arm is elevated. This is in congruence with the literature (Di Giacomo et al., 2008) Serratus anterior, later in the process, seems to enhance the degree of cooptation and upward rotation of the scapula, in order to prevent conflict between the acromion and the great tubercle of humerus.

In addition, the rotator cuff muscles main function is to provide stability to the joint by pressing the humeral head on the glenoid, mostly because of the limited stabilization afforded by the shallow glenoid and the variety of shoulder positions. The shoulder can maintain a stable fulcrum of motion only when it maintains balanced force couples in both the coronal and the transverse planes. The coronal plane force couple consists of the deltoid and supraspinatus, so that during the overhead motion, the resultant joint reaction force of the couple is directed towards the glenoid, improving stability. Subscapularis and infraspinatus transverse force couple is the predominant mechanism resisting superior humeral head displacement with cuff tears, being the responsible for the joint to remain centered and functional (Di Giacomo et al., 2008).

The clavicular portion of the pectoralis muscle was the only muscle that generated an ICC reported as excellent. The data from this muscle also demonstrated a large interquartile range, which is in line with previous literature reporting an increase in the ICC where there is great variability in the data.

The large variability described in terms of the scapulohumeral rhythm might explain the less repeatable upper and lower trapezius muscles scores. Current research would explain altered patterns of the former in SIS participants, although no consensus exist regarding altered patterns of muscle recruitment timing (Struyf et al., 2014). However the findings from the present study suggest they are one of the muscles with greatest variability, even in the healthy population, during the movement of abduction in the scapular plane.

The scapula is anatomically and biomechanically involved in shoulder function and movement of the arm. For the elevation of the glenohumeral joint to happen, the scapula rotates upwards, tilts to the back and rotates externally, as the humerus elevates and rotates externally. Most motion occurs in the glenohumeral and scapulothoracic joints. Generally, the glenohumeral to scapulotoracic motion ratio, of total shoulder motion is 2:1, i.e. in 180ª of abduction, 120º of motion occurs in the glenohumeral motion and 60º on the scapulothoracic motion. The 2:1 ratio is an average over the entire range of motion, however it is not constant. In the initial portion of abduction glenohumeral motion predominates and the ratio is 4:4 (glenohumeral to scapulothoracic). As the shoulder moves beyond 90º of abduction, the glenohumeral to scapulothoracic motion ratio becomes 1:1 (Di Giacomo et al., 2008). Due to the importance of the scapulothoracic rhythm for glenohumeral movement, in future studies the possible existence of scapular dyskinesia will be further studied in all the included participants, using the protocol proposed by Huang et al. (2015), to avoid non symptomatological neuromuscular alterations of the scapulothoracic muscles and reduce the reported variability.

In the volleyball task, there is also pre-activation of the deltoid and infraspinatus, with a slightly different order from the scaption movement. Infraspinatus also seem to enhance the centering of the humeral head during the movement on the volleyball task; however supraspinatus was not pre-activated for this motion, as it was for the abduction movement. Lower trapezius was also preactivated to position the scapula for the overhead movement.

The low ICC results might be explained by the fact that the participants were not accustomed to the volleyball task; which was also a multijoint task. However they seem to behave in a much more repeatable pattern when compared to the abduction moment. It might be that the task is more demanding when compared to the functional single joint abduction movement and so the nervous system might function in a much more predictable pattern.

This consideration may be an important fact that needs to be further explored in future studies. The addition of a weight in the abduction task could improve the reliability of the data by increasing the challenge of the movement. It is also possible that this may result in changed motor patterns specific to this more demanding task. According to Ludewig and Cook (2000a), the changed pattern in the upper trapezius muscle, experienced by SIS patients, was only apparent when the 4.6kg load was applied.

There were no differences between trials, with the exception of the clavicular portion of the pectoralis muscle, a muscle that has been shown to be less important for both analyzed movements. Generally the protocol showed good consistency and fewer trials are needed in the final study. The protocol also showed fair to good reliability and repeatability indexes for primer movers and lower coefficients for the muscles non-essentials for the analyzed motions. One explanation is the effect of a small sample for the EMG study (*n*=14).

The nature of the unconstrained functional tasks made the protocol prone to more variation for the muscles that were not the prime movers or synergists. Vasseljen et al. (2012), had similar results when studying the abdominal muscles.

Since the literature is not clear on the data from asymptomatic populations (Heuberer et al., 2015), the present study adds new knowledge in this areas of research. Moreover, the literature isn’t clear on the effect of SIS on proprioception and motor control. Further rehabilitation programs are anchored on the premise of restoration of normal patterns of movement, despite the fact that no established consensus exists in the literature regarding normal shoulder muscle onset timing or alterations from this pattern in participants with SIS (Struyf et al., 2014). Therefore, establishing a valid database of normal data will facilitate the assessment of the effectiveness of existing and new treatments.

Nevertheless, if there is asymmetry in the nature of connective tissue associated with a particular joint, this imbalance usually leads to an asymmetrical recruitment of the muscles associated with that joint (Criswell, 2011) and so, alterations on the motor strategies could be hypothesized.

Previous research provided evidence that patients with muscle pain may have changed patterns of motor control (Birch, Graven-Nielsen, Christensen, & Arendt-Nielsen, 2000; Madeleine, Lundager, Voigt, & Arendt-Nielsen, 2003; Sterling, Jull, & Wright, 2001). Furthermore, the pain-adaptation model defends a decreased activity of the agonist and an increased activity of the antagonist, with reduced range and velocity of the movement (Lund et al., 1991). In line with previous findings Diederichsen et al. (2009), also found that during arm elevation (abduction), the middle deltoid decreased their activity while latissimus dorsi increased theirs, on the symptomatic side, compared to the healthy shoulders. Although the precise nature of this effect remains unclear (Birch, Christensen, Arendt-Nielsen, Graven-Nielsen, & Sogaard, 2000) and needs to be further studied.

In fact, the literature although scarce, has proposed the notion that there is no difference in scapulothoracic muscle recruitment pattern between SIS and controls (Wadsworth and Bullock-Saxton, 1997, Moraes et al., 2008) and the only reported difference (Roy et al., 2008) being a delayed lower trapezius in SIS patients. The lower trapezius presented a delay of 69.1ms and it is possible that the present study is not able to detect these small differences between groups. The Bland and Altman results for the lower trapezius represent a much wider interval. It is however worthy of noting that the reported study was methodologically different from the present study. It included a reaching task in line with the contralateral foot. So perhaps, in the future, analysis of other EMG components, namely the frequency spectrum and the magnitude of the signal, could give more information on differences between groups and the effective contribution of each muscle for the functional movement.

7.2 IMPLICATIONS FOR FUTURE STUDIES

In order to be able to use this research in applied clinical settings, further refinement and testing of measurement protocols is required. Although some limitations have been addressed in the previous and present chapters, future work will need to consider them further. In particular further EMG data analysis of the frequency and magnitude domain, using a resistance to make the functional movement more challenging to the neuromuscular system and a velocity constrained movement for position sense evaluation will be explored. Skinfold evaluations of each participant will ensure body fat isn't impeding the data collection, which in turn will result in less noise in the data.

The production of reliable and valid measurement protocols will enable further research within a clinical population, to establish changes in proprioception and neuromuscular control in patient groups, namely patients with SIS, which will be investigated and compared to matched asymptomatic participants.

In clinical terms, the implications of these future studies will aid the development of targeted rehabilitation towards motor control strategies, to perform everyday work, with active recentering of the humeral head, avoiding encroachment and pain. It will also inform whether the condition develops a global response, and so both shoulders should be targeted, or whether it is a local problem. Furthermore, it will also inform the physiotherapist whether only scapular muscles should be targeted or if glenohumeral muscles, like the adductors, should be the center of attention.

A study of this nature, focusing on both afferent proprioceptive feedback and the efferent neuromuscular response, will shed light into the mechanisms of shoulder injury and will allow the development of prevention and treatment programs.

7.3 OVERALL CONCLUSIONS

The first aim of the present study was to establish normal patterns of proprioception in the shoulder and to achieve this, it was necessary to develop reliable methods to measure shoulder position sense and force reaction to an acceptable degree of accuracy. There were no differences in terms of position accuracy between angles for position sense and consequently, there were no tendency for greater or smaller error with increase of the angle of the joint. Furthermore all participants underestimated the reference angle. There were also no differences between trials. The relative reliability of joint position sense measures was found to be low and the repeatability was poor. This may have been due to a low level of between participant variance in the data and the nature of the velocity unconstrained movement. Further studies are needed to explore the reliability and repeatability of the measurements. For force reaction, the participants underestimated the target force and an increase in the amount of errors was found as the shoulder moved away from the neutral position for the internal rotators muscles. The opposite is true for external rotators. The ICCs were excellent, whilst the best repeatability scores were for internal rotation, at middle range. External rotators demonstrated lower repeatability scores. In general the protocol was found to be repeatable and reliable.

The second aim was to establish normal patterns of motor control and measure the natural variance in muscle onset timing in the shoulder. To achieve this it was necessary to develop reliable methods to measure shoulder motor control accurately. Overall there was pre-activation of all portions of the deltoid muscle, supraspinatus, infraspinatus and serratus anterior muscles, in the movement of abduction in the scapular plane. The volleyball task presented pre-activation of all portions of the deltoid muscle, infraspinatus and lower trapezius. There were no differences between trials, with the exception of the clavicular portion of the pectoralis muscle for the abduction in the scapular plane movement. While relative coefficients of reliability were poor, repeatability was good for prime movers. Changes in muscle onset timing of muscles that are not agonists or synergists for the desired movement were found to be more variable. Small changes in the timing of muscle onset of the prime movers and synergists can be interpreted as meaningful. Muscles that are not agonists or synergists for the desired movement are more variable, and less meaningful. In general the procedures to evaluate muscle onset timing have demonstrated good consistency and repeatability.

Future work will investigate the use of these tools on populations of patients with SIS to quantify the mechanical impingement and movement patterns as potential mechanisms for the development of shoulder pain. This will involve investigations of homogenous patient groups, with subgrouping according to diagnostic tests (Cools et al., 2008) and classification based on specific movement patterns. Diagnosis based on detailed analysis of movement may allow more effective subgrouping of patients to guide treatment strategies (Braman et al., 2014b).

Future work will also inform physiotherapy practice by contributing to the understanding about whether SIS patients develop new strategies to overcome the condition. Further work will also answer clinical questions about which muscles should be targeted for treatment and whether glenohumeral muscles should be included in treatment plans in addition to scapular muscles which are presently the focus of management strategy for these patients.

GLOSSARY OF TERMS

sEMG – Surface EMG

IKD – Isokinetic

JPS – Joint Position Sense

FR – Force Reproduction

SP0.1 – Joint Position Sense for 0º. First Trial

SP0.2 – Joint Position Sense for 0º, Second Trial

SP0.3 – Joint Position Sense for 0º. Third Trial

SP45.1 – Joint Position Sense for 45º. First Trial

SP45.2 – Joint Position Sense for 45º, Second Trial

SP45.3 – Joint Position Sense for 45º. Third Trial

SP80.1 – Joint Position Sense for 80º. First Trial

SP80.2 – Joint Position Sense for 80º, Second Trial

SP80.3 – Joint Position Sense for 80º. Third Trial

T0 – Toward, 0º; Internal Rotation at 0º

T45 – Toward 45º, Internal Rotation at 45º

T80 – Toward 80º, Internal Rotation at 80º

A0 – Away 0º, External Rotation at 0º

A45 – Away 45º, External Rotation at 45º

A80 – Away 80, External Rotation at 80º

Glossary of Muscles Nomenclature:

B – Biceps

DA – Deltoid Anterior

DM – Middle Deltoid

DP – Deltoid Posterior

GD – Latissimus Dorsi

Ip – Infraspinatus

LT – Lower Trapezius

PC – Pectoral, clavicular portion

PE – Pectoral, external portion

RM – Teres Major

Serr – Serratus Anterior

Sp – Supraspinatus

UT – Upper trapezius

Statistical Terms Glossary

CI – Confidence interval

LB – Lower Bound

UB – Upper Bound

B&A – Bland and Altman coefficient of repeatability

SEM – Standard error of measurement

MD – Minimum difference

MAV – Mean Amplitude Value

SD – Standard Deviation

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APPENDIX 1 – CONSENT FORM AND PARTICIPANT INFORMATION SHEET

This document will be translated into Portuguese

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CONSENT FORM

Title of Project: Shoulder proprioception and motor control

Name of Researchers: Sandra Rodrigues; Lucy Redhead, Anne Mandy

1. I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without any reason, without my medical care or legal rights being affected. ☐
3. I am aware of my requirements within the study. ☐
4. I have read and understand the Participant Information Sheet (version 1) ☐
5. I agree to take part in the above study. ☐

____________________ ____________ ______________________________
Name of Patient Date Signature

____________________ ____________ ______________________________
Researcher Date Signature

This document will be translated into Portuguese

PARTICIPANTS INFORMATION SHEET

1 Study title

Shoulder Proprioception and Motor

2 Invitation paragraph

You are being invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Thank you for reading this.

3 What is the purpose of the study?

The purpose of this research is to study shoulder proprioception and motor control in healthy participants. Under these assumptions, want to study the sense of position of your arm, your ability to produce a certain amount of force and how your muscles react during specific target oriented movements.

4 Why have I been chosen?

You have been invited because you are a student member of University Fernando Pessoa.

You will not be able to participate if you have any of the following:

- Fracture of the arm
- Any history of problems with your shoulder
- Hypermobility
- Pregnancy

5 Do I have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time without giving a reason. A decision to withdraw at any time, or a decision not to take part, will not affect you in any way.

6 What will happen to me if I take part?

- You will be asked to visit University Fernando Pessoa Performance Lab on a single occasion and the session in the laboratory will last approximately one hour and a half;
- You will be asked to provide some demographic information;
- You will be asked to perform some target oriented movements and a small device will attached to your arm to record muscle activity;
- You will be asked to perform some tests in an exercise machine. Those tests will include perception of shoulder position, muscle strength and activation;
- None of the previously explained procedures will cause pain or any discomfort.

- These are all standard and widely used techniques,

7 What do I have to do?

To eliminate the effects of muscular fatigue on joint position sense, you will be asked not to practice any kind of sport for at least one day prior to testing.

8 What are the possible disadvantages and risks of taking part?

During this study instruments to measure muscle contractions will be attached to your skin using medical tape. It is possible that some people may develop a mild allergic reaction to this tape. If this happens, we will remove the tape immediately. It will be asked about possible allergies before commencing the study.

9 What are the possible benefits of taking part?

The information we get from this study may help us to understand more about how the shoulder works. It is also a benefit for you to have your shoulder neurophysiology assessed for free and you may have access to the results of your tests if you so wish.

10 What if something goes wrong?

If you have any questions, please don’t hesitate to contact the researcher or supervisors. You will be given a copy of the signed consent form to keep, and within this document you can find information about the supervisors.

11 Will my taking part in this study be kept confidential?

The information provided by you will be kept confidential and no other person besides the research team will have access to your personal information.

12 What will happen to the results of the research study?

Although is our purpose to publish the results of this study, the information provided by you will be kept confidential, this way you will not be identified in any report/publication.

13 Who has reviewed the study?

This study has been reviewed by both University of Brighton Ethics Committee and Universidade Fernando Pessoa Ethics Committee.

14 Contacts for Further Information

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APPENDIX 2 – SAMPLE CARACHTERIZATION QUESTIONAIRE

Universidade Fernando Pessoa
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SAMPLE CARACHTERIZATION QUESTIONAIRE – Normative data

__/__/2012

1 Name: ____________________________ Student No: _______ Date of birth: __ / __ / ____

2 Please, select as appropriate:

Gender: M __ F __

Pregnancy: Yes __ No __

Sports practice: Yes __ No __, Present __ Past __

If yes, please describe: __________________________________

Did you practice some sports in the previous 24h? Day 1: Yes __ No __

Day 2: Yes __ No __

Previous history of

Shoulder pain in the previous 24h? Yes __ No __,

If yes, please describe: ________________________________

Upper limb calcification or fracture: Yes __ No __

Shoulder instability: Yes __ No __

Shoulder surgery: Yes __ No __

Shoulder pain during neck movements: Yes __ No __

Neurological disorder: Yes __ No __

Other(s) pathological condition(s): ____

3 Tests:

Shoulder instability:

- Positive sulcus: Yes __ No __
- Positive relocalisation test: Yes __ No __

Laxity:

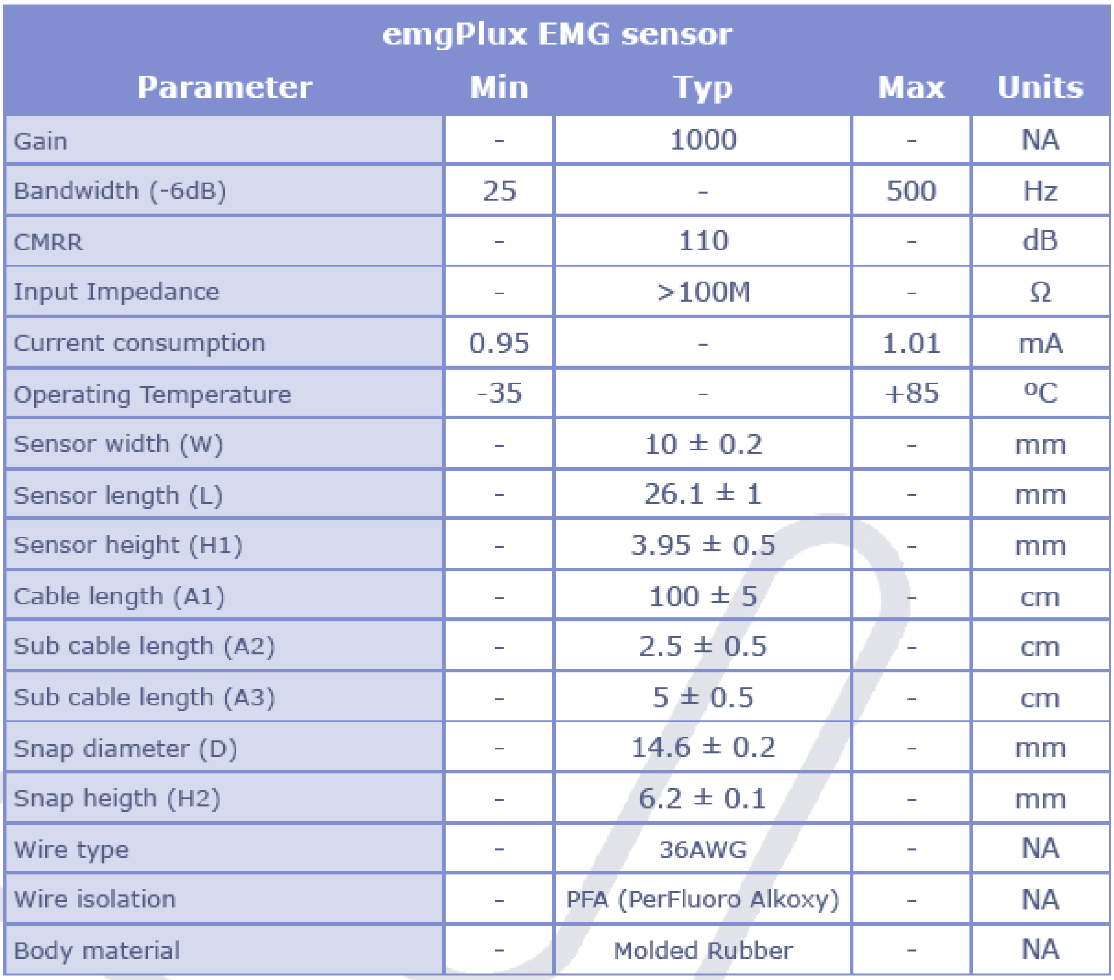
- Thumbforearm sign: Yes __ No __
- Elbow recurvatum
  Right: Yes __ No __
  Left: Yes __ No __
  Previous history of elbow injury: Yes __ No __
- Hyperextension of metacarpophalangeal joints: Yes __ No __

APPENDIX 3 – POSITION SENSE AND FORCE REACTION INDIVIDUAL DATA

	Positional Sense 0º					Positional Sense 45º					Positional Sense 80º				
	PS.0.1	PS.0.2	PS.0.3	Mean	SD	PS.45.1	PS.45.2	PS.45.3	Mean	SD	PS.80.1	PS.80.2	PS.80.3	Mean	SD
1	5,7	-2,3	-4,4	-0,33	5,33	-10,2	-10,5	-0,7	-10,63	10,00	-10,8	-9,2	-4,8	-8,27	3,11
2	3,4	-0,8	7	3,20	3,90	2,7	-1,2	20,6	6,97	11,88	-8,2	1,6	-4,1	-3,57	4,92
3	-0,2	-4,5	5,4	0,23	4,96	20,7	-3,1	5,9	6,80	10,38	12,7	-11,6	-0,6	0,17	12,17
4	-8,8	-0,9	-3,6	-4,43	4,02	-6,6	-5,6	-2,7	-6,83	4,87	6,6	13,6	3,6	7,93	5,13
5	10,5	-7,9	4,9	2,50	9,43	-14,5	6,9	3,6	0,97	7,60	-0,1	3,4	-11,6	-2,77	7,85
6	-4,7	-1,5	-2,9	-3,03	1,60	4,2	-1,9	-2,2	-0,60	2,52	-1,1	3,7	-0,8	0,60	2,69
7	-4,5	-1,1	1,1	-1,50	2,82	-15,9	6,5	7,8	1,63	9,58	-0,8	3,9	7,3	3,47	4,07
8	-5,1	-13,5	-4,8	-7,80	4,94	11,8	-11,5	-2,8	-4,67	6,12	7	5,7	12,2	8,30	3,44
9	-15,5	-9,3	-7,2	-10,67	4,32	0,8	-1,3	6,9	1,70	4,52	3,5	-4,7	2,8	0,53	4,55
10	-2,7	2,5	-5,7	-1,97	4,15	19	-13,7	-2,4	-3,60	9,56	-1,9	7,2	-1,6	1,23	5,17
11	0,9	-0,4	2,2	0,90	1,30	3,1	-2,9	8,4	1,90	5,84	8,3	8,1	4,5	6,97	2,14
12	-5,8	-8	-8,2	-7,33	1,33	-5,6	-4,9	-8,9	-8,10	2,88	3,3	1,4	-4,7	0,00	4,18
13	-8	-4,6	-4	-5,53	2,16	-4,4	-8,2	-4,8	-8,53	3,91	4,7	7,8	5	5,83	1,71
14	-8,5	-0,7	-0,4	-3,20	4,59	-13	0,1	-9,9	-7,57	6,81	-11,9	-5,2	8,1	-3,00	10,18
15	7,3	-6,5	4,3	1,70	7,26	-2,5	-6,2	-5,1	-6,67	1,84	7,9	-11,6	6,6	0,97	10,90
16	-5,1	5,7	-4,2	-1,20	5,99	-11	7,6	7,6	3,93	6,35	-19,2	3,3	-15,1	-10,33	11,98
17	-10,4	-6,9	0,4	-5,63	5,51	-1,9	-9,1	-9	-9,70	1,13	-5,9	-3,9	-4,7	-4,83	1,01
18	-6,5	2,6	-3,3	-2,40	4,62	6,3	-4	-5,8	-2,50	4,25	0,7	5,3	4,6	3,53	2,48
19	-6,2	7,9	1,1	0,93	7,05	-7,7	-9,8	-5,5	-10,93	6,08	-8,3	0,6	0,4	-2,43	5,08
20	-6,5	5,9	-4,2	-1,60	6,60	-6,2	-6,8	-2	-7,27	5,51	-3,7	-16,7	-0,1	-6,83	8,73
21	0,4	12,5	-1,1	3,93	7,46	-5,6	5,9	-3,2	1,00	4,59	2,3	-1,4	4,7	1,87	3,07
22	1,8	-7	-4,2	-3,13	4,50	4,1	12,9	5,1	11,67	6,05	7,1	5,2	10	7,43	2,42
23	-6,6	-2,6	-9	-6,07	3,23	-1,7	-3	-1,9	-3,20	1,41	2,9	1,9	-3	0,60	3,16
24	-0,9	7,1	7,6	4,60	4,77	7,7	-2	-3,2	0,17	4,83	-8,7	-11,2	-11,1	-10,33	1,42
25	-11,9	0,2	-4,3	-5,33	6,12	7,8	-19,7	-9,6	-13,73	5,29	-11,4	-19,5	-15,5	-15,47	4,05
26	-10,2	-6,7	-10	-8,97	1,97	-10,4	-8	4,7	-7,23	11,57	2,8	-0,5	-3,7	-0,47	3,25
27	3,6	-0,1	-8,8	-1,77	6,37	-5,3	9,7	-1,8	4,10	5,76	10,9	3,2	-4,4	3,23	7,65
28	-3,5	-3,6	4,4	-0,90	4,59	-10,7	4,5	-12,4	-4,70	8,55	-2,2	7,5	-0,4	1,63	5,16
29	-7,8	0,2	4,9	-0,90	6,42	-9,8	1,9	-0,7	-2,23	5,08	-2,2	3,6	-1,2	0,07	3,10
30	-0,6	-3,8	3,7	-0,23	3,76	-1,8	-5,8	-4,8	-6,07	1,42	-12,8	-9,8	-3,4	-8,67	4,80
31	-9,6	0,6	7,6	-0,47	8,65	-14,1	-0,5	4,3	-3,60	9,82	-3	8,8	19,8	8,53	11,40
32	-8,7	-4	1,5	-3,73	5,11	1,1	1,6	-3,7	0,20	3,42	-0,7	-5	5,2	-0,17	5,12
			Mean	-2,19				Mean	-2,73				Mean	-0,44	
			SD of the Mean	3,70				SD of the Mean	5,88				SD of the Mean	5,91	

	T0º						T45º						T80º						A0º						A45º						A80º					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
1	-0,27	-0,2	1,72	2,06	0,8275	1,235027	-0,2	-0,21	-0,23	-0,47	-0,2775	0,128938	-0,21	-1,15	-2,03	-2,14	-1,3825	0,898494	-0,16	-2,94	-3,95	-3,15	-2,55	1,651686	-0,24	0,65	0,71	0,04	0,29	0,46526	-0,14	-0,45	0,34	0,81	0,14	0,552389
2	-1,27	-1,34	-0,81	-0,45	-0,9675	0,417483	-0,21	-0,7	-1,4	-1,32	-0,9075	0,560439	-0,38	-0,34	-0,44	-0,43	-0,3975	0,046458	-1,26	-0,36	-0,71	-1,43	-0,94	0,493896	-2,11	2,09	0,88	-1,62	-0,19	2,006207	-0,11	0,98	1,83	1,46	1,04	0,841942
3	0,12	-0,11	0,19	0,19	0,0975	0,142215	-0,2	-1,26	-0,37	-0,71	-0,635	0,467511	-0,25	-1,74	-1,28	-0,8	-1,0175	0,639603	-1,02	-3,31	-1,95	-2,17	-2,1125	0,941147	-0,39	2,43	0,46	0,38	0,72	1,202691	-0,17	-0,11	0,9	0,33	0,2375	0,494731
4	-0,43	-1,29	-1,7	-1,81	-1,3075	0,626332	-0,84	-0,98	-0,64	-1,5	-0,99	0,367514	-1,94	-0,42	-1,47	-2,13	-1,49	0,765376	-2,37	-3,06	-3,86	-4,23	-3,38	0,831745	-2,41	-2,48	-2,27	-2,89	-2,5125	0,26638	-0,28	0,61	0,01	-1,64	-0,325	0,951788
5	-0,18	-1,08	-1,34	-1,6	-1,05	0,61763	-0,22	-0,19	-0,14	-0,1	-0,1625	0,053151	-0,37	-2,09	-2,51	-3,19	-2,04	1,202054	-2,07	-3,29	-1,61	-4,65	-2,905	1,36229	-1,69	-1,01	2,56	4,92	1,195	3,105055	-3,37	1,61	0,38	0,51	-0,2175	2,172884
6	0,26	0,06	-0,45	-0,45	-0,145	0,361525	-0,2	-0,55	-0,04	0,71	-0,02	0,531225	-0,24	-0,55	-1,04	-1,7	-0,8825	0,636782	-1,11	1,78	2,03	-0,9	0,45	1,685368	-0,88	-2,2	-1,47	-1,19	-1,435	0,564063	-0,12	0,94	0,16	0,51	0,3725	0,457775
7	-0,2	-1,26	-1,16	-1,2	-0,955	0,505008	-0,3	0,3	0,39	1,28	0,4175	0,651479	-0,23	2,27	2,8	1,08	1,48	1,347912	-2,07	-3,27	-2,67	-3,85	-2,965	0,766877	-0,77	-0,68	-1,23	-0,52	-0,8	0,30474	2,3	6,8	6,87	4,02	4,9975	2,235119
8	-0,04	1,29	1,25	0,85	0,8375	0,617812	-0,4	-0,58	-0,45	-0,15	-0,395	0,180093	-0,19	-2,3	-3,72	-1,99	-2,05	1,450816	-0,84	-2,9	-3,81	-3,63	-2,795	1,361433	-0,2	-1,58	-3,88	-2,28	-1,985	1,53061	-0,18	-0,71	0,5	-0,25	-0,16	0,498865
9	-0,2	2,24	1,13	1,06	1,0575	0,997476	-0,14	0,71	-1,8	-1,74	-0,7425	1,236403	0,11	0,4	0,93	-1,46	-0,005	1,0277	-0,35	-3,49	-4,35	-4,37	-3,14	1,904696	-1,47	-3,11	-3,73	-4,79	-3,275	1,388944	-0,23	-1,26	-1,39	1,64	-0,31	1,399738
10	1,52	0,87	0,82	0,73	0,985	0,36134	-1,51	-1,7	-2,51	-2,47	-2,0475	0,517067	-0,76	-1,73	-2,08	-1,05	-1,405	0,606438	-0,31	0,27	0,73	0,89	0,395	0,538486	-0,26	-4,61	-3,36	-3,48	-2,9275	1,865357	-0,08	0,07	1,74	1,53	0,815	0,952698
11	0,96	0,1	0,31	0,93	0,575	0,435928	-0,39	-0,54	-1,45	-1,38	-0,94	0,55263	-0,24	-0,82	-1,46	-1,64	-1,04	0,638957	-0,63	-2,18	-2,05	-1,8	-1,665	0,70779	-0,42	-0,76	-0,41	-1,07	-0,665	0,315225	-0,1	-0,5	-1,1	-1,76	-0,865	0,7245
12	0,62	1,56	2,39	2,43	1,75	0,853424	-0,2	0,39	0,09	0,01	0,0725	0,244455	-0,45	-0,54	-1,28	-0,59	-0,715	0,381095	-0,36	-0,98	-1,8	-1,79	-1,2325	0,697107	-0,64	-0,53	-1,44	-2,01	-1,155	0,699547	0,01	1,96	2,31	2,09	1,5925	1,064843
13	-0,11	-1,46	-2,58	-2,7	-1,7125	1,20547	-0,19	0,77	0,39	0,99	0,49	0,516656	-0,59	0,59	0,6	2,08	0,67	1,093465	-1,08	-3,95	-3,75	-3,43	-3,0525	1,332326	-0,26	-0,85	0,75	1,81	0,3625	1,169484	-0,15	1,73	4,28	5,55	2,8525	2,555339
14	0,18	3,38	2,35	3,59	2,375	1,560438	0,03	1,26	1,12	0,49	0,725	0,571693	-0,31	-0,02	-1,64	-0,63	-0,65	0,705455	-0,3	0,11	-1,26	-2,1	-0,8875	0,991476	-0,89	1,89	-0,29	-0,62	0,0225	1,268946	-0,25	5,86	5,3	6,32	4,3075	3,066827
15	-0,08	0,08	-0,34	-0,39	-0,1825	0,221566	-0,2	-1,37	-1,65	-0,73	-0,9875	0,65107	-0,22	0,18	0,74	-0,08	0,155	0,423753	-0,44	0,98	-2,58	-2,45	-1,1225	1,710056	-0,27	2,76	1,11	-1,43	0,5425	1,806495	-0,05	-0,01	-0,63	-0,58	-0,3175	0,333004
16	-0,45	-0,11	-0,37	-0,36	-0,3225	0,147281	-0,59	-0,87	-0,88	-1,07	-0,8525	0,197716	-0,48	-0,5	-0,34	-1,05	-0,5925	0,313196	-0,83	-1,48	-2,1	-1,7	-1,5275	0,531123	-0,43	-0,18	-0,31	-0,29	-0,3025	0,102429	-0,23	0,96	0,15	0,84	0,43	0,566569
17	-0,03	1,62	3,94	3,5	2,2575	1,82699	-0,23	-0,01	-0,42	-0,2	-0,215	0,167829	-0,32	-3,05	-3,52	-3,56	-2,6125	1,545777	-0,6	-3,79	-2,35	-4,27	-2,7525	1,650704	-0,42	-0,55	-1,67	-1,81	-1,1125	0,72876	-0,15	-0,52	0,97	0,01	0,0775	0,635052
18	-0,1	-0,03	0,31	0,74	0,23	0,384274	-0,2	-0,36	-0,41	-0,42	-0,3475	0,101776	-0,45	-0,69	-1,83	-0,68	-0,9125	0,621631	-2,57	-1,88	-3,17	-3,98	-2,9	0,8923	-0,19	1,35	1,84	3,14	1,535	1,375851	-0,14	0,76	0,78	1,39	0,6975	0,630258
19	0,08	-0,37	-0,09	1,13	0,1875	0,655153	-0,76	0,26	1,22	1,4	0,53	0,994987	-1,12	-0,28	-0,29	0,12	-0,3925	0,521241	-1,4	-1,17	-1,49	-2,56	-1,655	0,618196	-0,4	-0,85	1,55	2,09	0,5975	1,440495	-0,29	-0,88	-0,63	-0,72	-0,63	0,249132
20	-0,44	-2,34	-1,96	-1,89	-1,6575	0,835399	-0,27	-0,42	-1,21	-0,66	-0,64	0,412553	-0,44	-2,34	-1,96	-1,89	-1,6575	0,835399	-0,58	-1,94	-3,45	-3,77	-2,435	1,47179	-0,18	0,42	-2,03	-0,54	-0,5825	1,043084	-0,29	-0,15	1,28	0,7	0,385	0,739842
21	0,15	0,34	0,31	0,4	0,3	0,106771	-0,64	-0,26	-0,39	-0,07	-0,34	0,239305	-0,46	-0,57	-1,06	-1,93	-1,005	0,669552	-2,77	-2,79	-2,34	-4,07	-2,9925	0,747724	-0,25	-1,9	-1,47	-0,91	-1,1325	0,71444	-0,18	-0,64	-0,26	0,63	-0,1125	0,534127
22	-0,05	1,05	1,69	2,23	1,23	0,980204	-0,48	0,26	-0,29	-0,2	-0,1775	0,314152	-0,22	-1,37	-3,02	-2,46	-1,7675	1,238423	-1,47	-1,75	-2,24	-2,49	-1,9875	0,462052	-0,59	-0,63	-0,37	-0,17	-0,44	0,213229	-0,22	0,68	1,99	1,05	0,875	0,914859
23	-0,32	1,36	1,8	2,21	1,2625	1,110627	-0,2	-0,35	-0,39	-0,4	-0,335	0,092556	-0,2	-0,63	-2,09	-2,68	-1,4	1,175783	-0,86	-1,91	-0,66	-1,84	-1,3175	0,649532	-1,16	-1,39	-2,08	-2,35	-1,745	0,561694	-0,1	-0,71	-0,53	-0,39	-0,4325	0,257472
24	-0,15	1,12	1,42	1,17	0,89	0,705644	-0,15	-0,5	-0,06	-0,04	-0,1875	0,213756	-0,3	-2,68	-4,15	-2,9	-2,5075	1,60776	-2,79	-4,6	-3,88	-3,08	-3,5875	0,817369	-0,39	-3,92	-3,25	-3,25	-2,7025	1,573687	-0,32	1,3	3,02	2,7	1,675	1,525374
25	-0,17	-0,76	-1,25	-0,6	-0,695	0,446057	-0,24	-0,07	-1,84	-1,4	-0,8875	0,867463	-0,73	-1,15	-2,83	-3,21	-1,98	1,222947	-0,54	-1,22	-2,61	-1,8	-1,5425	0,878422	-0,24	-0,53	-1,76	-0,18	-0,6775	0,737671	-0,21	-1,07	-0,92	0,02	-0,545	0,53157
26	-0,1	0,3	-0,08	-0,02	0,025	0,186458	-0,1	-0,1	-0,1	-0,1	-0,1	0	-0,18	-0,38	-1,17	-1,25	-0,745	0,544089	-0,23	1,23	1,28	0,51	0,6975	0,711401	-0,15	1,74	1,3	0,49	0,845	0,841447	-0,13	-0,19	-0,21	0,04	-0,1225	0,113541

APPENDIX 4 – EMGPLUX SPECIFICATIONS



emgPlux EMG sensor				
Parameter	Min	Typ	Max	Units
Gain	-	1000	-	NA
Bandwidth (-6dB)	25	-	500	Hz
CMRR	-	110	-	dB
Input Impedance	-	>100M	-	Ω
Current consumption	0.95	-	1.01	mA
Operating Temperature	-35	-	+85	ºC
Sensor width (W)	-	10 ± 0.2	-	mm
Sensor length (L)	-	26.1 ± 1	-	mm
Sensor height (H1)	-	3.95 ± 0.5	-	mm
Cable length (A1)	-	100 ± 5	-	cm
Sub cable length (A2)	-	2.5 ± 0.5	-	cm
Sub cable length (A3)	-	5 ± 0.5	-	cm
Snap diameter (D)	-	14.6 ± 0.2	-	mm
Snap heigth (H2)	-	6.2 ± 0.1	-	mm
Wire type	-	36AWG	-	NA
Wire isolation	-	PFA (PerFluoro Alkoxy)	-	NA
Body material	-	Molded Rubber	-	NA

Figure 1. EMGPlux sensor characteristics

APPENDIX 5 – ELECTRODES PLACEMENT FOR EACH MUSCLE

UPPER TRAPEZIUS (SPECIFIC)

Action: Adduction, upward rotation, and elevation of the scapula: side bending of head

Muscle Insertions: the upper fibres of the trapezius arise from the superior nuchal line, the external occipital protuberance, and the ligamentum nuchae. They insert on the lateral third of the clavicle and the spine of the scapula.

Innervation: C3-C4

Location: placement of 2 active electrodes (2 cm apart) so that they run parallel to the muscle fibres, one half the distance between the cervical spine at C7 and the acromion.

Behavioral test: shoulder elevation, lateral bending of the head.

Volume conduction: Middle fibres of trapezius, levator scapula, supraspinatus

Artifacts: ECG, breathing

LOWER TRAPEZIUS (QUASI-SPECIFIC)

Action: Scapular stabilization, upward rotation, retraction and depression of the scapula during abduction and flexion

Muscle Insertions: The fibres arise from T3 to T12 and insert on the scapular spine

Innervation: Spinal portion of the accessory nerve (eleventh cranial nerve), ant the ventral ramus C2, C3 and C4

Location: Palpate the inferior medial border of the scapula for the muscle mass that emerges. Place the electrodes on an oblique angle, approximately 5cm down from the scapular spine. The two active electrodes (2cm apart) are placed next to the medial edge of the scapula at a 55 degree oblique angle

Behavioral test: Abduction of arms, retraction of the shoulder back and down at a 45 degree angle

Volume conduction: Middle trapezius, rhomboids and erector spinae

Artifacts: ECG, breathing

SERRATUS ANTERIOR, LOWER FIBRES (SPECIFIC)

Action: Upward rotation, depression, and abduction of the scapula during abduction and flexion of the arm. Protraction of the scapula during pushing activities

Muscle Insertions: The fibres of this multibelled muscle usually arise by nine slips from the firth to ninth ribs. The lowest portion of this muscle inserts on the costal surface of the inferior angle of the scapula

Innervation: The anterior rami of the C5 through C8 spinal nerves

Location: The participant should flex the arm against resistance. The two active electrodes should be placed horizontally (2 cm apart) just below the axillary area and anterior to the border of the latissimus dorsi muscle at the level of the inferior tip of the scapula.

Behavioral test: Forward flexion of the arms, protraction of the shoulders, push-ups

Volume conduction: latissimus dorsi, intercostal muscle, costal portion of pectoralis

Artifacts: ECG, respiration

SUPRASCAPULAR FOSSA (UPPER TRAPEZIUS/SUPRASPINATUS) PLACEMENT (QUASI-SPECIFIC)

Action: Abduction of the arm, controls the head of the humerus in the glenoid fossa

Muscle Insertions: The fibres of supraspinatus lie beneath middle and upper fibres of the trapezius. They arise from the supraspinatus fossa and insert on the greater tubercle of the humerus.

Innervation:

Location: After palpating the spine of the scapula and locating its lateral distal aspect, the electrodes should be placed 2cm apart, directly above the spine of the scapula, over the suprascapular fossa.

Behavioral test: Abduction of the arm

Volume conduction: Major problems of cross-talk arise from the middle and upper fibres of the trapezius. It is impossible to isolate EMG activity from the supraspinatus (relative to the upper trapezius) with surface electrodes. These muscles are layered next to each other and function synergistically. Movements that attempt to separate out differential muscle function fail to show differential recruitment patterns from the upper trapezius at this site.

Artifacts: ECG

INFRASPINATUS (SPECIFIC) + TERES MINOR

Action: Lateral rotation of the shoulder joint, along with stabilization of the head of the humerus in the glenoid cavity.

Muscle Insertions: The fibres arise from the infraspinatus fossa, below the spine of the scapula, and insert on the greater tubercle of the humerus.

Innervation: The superior cord of the brachial plexus, from the spinal nerves of segments C4, C5 and C6

Location: after palpating the spine of the scapula two active electrodes were placed 4 cm below the spine of the scapula and parallel to it. Placement above posterior deltoid should be avoided

Behavioral test: Lateral rotation; abduction of the arm

Volume conduction: posterior deltoid, teres major and teres minor

Artifacts: ECG

DELTOID ANTERIOR (SPECIFIC)

Action: Forward flexion, medial rotation and abduction of the arm

Muscle Insertions: This muscle arises from the lateral third of the clavicle and inserts on the deltoid tuberosity of the humerus

Innervation: Via the axillary nerve from the posterior cord of the brachial plexus (these carry fibres from the spinal nerves of segments C5 and C6

Location: After palpating the clavicle, two active electrodes, 2 cm apart, are placed on the anterior aspect of the arm, approximately 4 cm below the clavicle, so that they run parallel to the muscle fibres

Behavioral test: forward flexion, abduction, and horizontal adduction of the arm

Volume conduction: medial deltoid, biceps, and pectoralis major

Artifacts:

MIDDLE DELTOID (SPECIFIC)

Action: Abduction of the arm

Muscle Insertions: This muscle arises from the acromion and inserts on the deltoid tuberosity of the humerus

Innervation: the axillary nerve, spinal segments C5 and C6

Location: The active electrodes are placed on the lateral aspect of the upper arm, 2 cm apart, and approximately 3 cm below the acromion, over the muscle mass so that the electrodes run parallel to the muscle fibres

Behavioral test: abduction of the arm

Volume conduction: anterior and posterior deltoids, biceps and triceps

Artifacts:

DELTOID POSTERIOR (SPECIFIC)

Action: extension, lateral rotation and abduction of the arm

Muscle Insertions: this muscle arises from the lower border of the spine of the scapula and inserts on the deltoid tuberosity of the humerus

Inervation: the axillary nerve, spinal segments C5 and C6

Location: After palpating the spine of the scapula, two active electrodes are placed 2 cm apart and approximately 2 cm below the lateral border of the spine of the scapula and angled on an oblique angle toward the arm so that they run parallel to the muscle fibres

Behavioral test: extension, abduction, and lateral rotation of the arm

Volume conduction: middle deltoid, infraspinatus, teres major and triceps

Artifacts:

LONG HEAD OF BICEPS (SPECIFIC)

Action: Shoulder flexion, forearm flexion, supination

Muscle Insertions: The biceps is a two-bellied muscle. The long head arises from the superior margin of the supraglenoid tubercle of the scapula and passes over the head of the humerus. The short head arises from the coracoid process of the scapula. Both insert into the tuberosity of the radius.

Inervation: The musculocutaneous nerve via the lateral cord and spinal nerves C5 and C6

Location: After asking the participant to flex his or her forearm in the supinated position, the muscle mass has been palpated and two active electrodes have been placed laterally to the center of the mass, 2 cm apart, as it will emphasize detection of shoulder flexion in addition to forearm flexion.

Behavioral test: Flex the forearm

Volume conduction: brachialis, deltoid, triceps, forearm extensors

Artifacts:

PECTORALIS MAJOR, CLAVICULAR AND STERNA PLACEMENT (SPECIFIC)

Action: internal rotation and flexion of the shoulder, horizontal adduction of the arm; depression of the shoulder (sterna aspect)

Muscle Insertions: the clavicular aspect arises from the medial third of the clavicle. The sterna aspect arises from the sterna membrane and the cartilage of the second to sixth ribs. Both insert on the greater tubercle of the humerus

Inervation: This area is innervated by the medial and lateral pectoralis nerves. The clavicular aspect is innervated mainly via the C5 and C6 spinal nerves, the sterna aspect is innervated mainly via the C6 and C7 spinal nerves

Location: For clavicular placement, the clavicle had been palpated and two active electrodes (2 cm apart) were placed on the chest wall at an oblique angle toward the clavicle, approximately 2 cm below the clavicle, just medial to the axillary fold.

For sternal placement, the anterior axillary fold have been palpated and identified while the subject actively rotates the arm medially against resistance. The electrodes were placed 2 cm apart, horizontally on the chest wall over the muscle mass approximately 2 cm out from the axillary fold

Behavioral test: Flexion of the arm, abduction of the arm above 90º, medial rotation and horizontal adduction of the arm

Volume conduction: anterior deltoid, sterna or clavicular aspect of pectoralis major, pectoralis minor

Artifacts: ECG

DORSAL ANCHOR/LATISSIMUS DORSI PLACEMENT (SPECIFIC)

Action: medially (internally) rotates, adducts and extends the shoulder, it also participates in rotation, lateral bending and extension of the torso

Muscle Insertions: This very broad muscle arises from the lower six thoracic vertebrae, the lumbodorsal fascia, the sacrum and crest of the ilium, and the last three of four ribs, it inserts, along with the teres major, on the medial edge of the humerus

Inervation: the thoracodorsal nerve from the posterior cord of the brachial plexus via the spinal nerves of C6, C7 and C8

Location: after palpating the scapula, the two active electrodes are placed (2 cm apart) approximately 4 cm below the inferior tip of the scapula, half the distance between the spine and the lateral edge of the torso.

Behavioral test: extend, adduct or medially rotate the arm

Volume conduction: teres major, lower trapezius

Artifacts: ECG

TERES MAJOR, NO ELECTRODES PLACEMENT DESCRIPTION FOR THIS MUSCLE WERE FOUND

(Kendall et al., 2005)

Action: Medially rotates, adducts, and extends the shoulder joint

Muscle Insertions: it originates at the dorsal surface of the inferior angle and lower 1/3 of the lateral border of the scapula and inserts at the crest of the lesser tubercle of the humerus

Inervation: lower subscapular, C5, C6, C7

Location:

Behavioral test: extension and adduction of the humerus in the medially rotated position, with the hand resting on the posterior iliac crest

Volume conduction: dorsal anchor

Artifacts: ECG

APPENDIX 6 – NORMALITY TESTS

Tests of Normality

	Angle	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	DF	Sig.	Statistic	DF	Sig.
SP	SP0	,081	96	,127	,986	96	,420
	SP45	,060	96	,200[*]	,987	96	,465
	SP80	,080	96	,144	,981	96	,181

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Table 1. Tests of Normality for Joint Position Sense.

Test of Homogeneity of Variance

		Levene Statistic	df1	df2	Sig.
SP	Based on Mean	3,808	2	285	,023
	Based on Median	3,857	2	285	,022
	Based on Median and with adjusted df	3,857	2	260,953	,022
	Based on trimmed mean	3,802	2	285	,023

Table 2. Tests of of Homogeneity of Variances for Joint Position Sense.

Tests of Normality

	TowAD	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	DF	Sig.	Statistic	DF	Sig.
Toward	T0	,089	26	,200[*]	,976	26	,770
	T45	,116	26	,200[*]	,952	26	,257
	T80	,101	26	,200[*]	,969	26	,592

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Table 3. Tests of Normality for Force Reproduction, internal rotation methods.

Test of Homogeneity of Variance

		Levene Statistic	df1	df2	Sig.
Toward	Based on Mean	4,198	2	75	,019
	Based on Median	4,280	2	75	,017

	Based on Median and with adjusted df	4,280	2	66,145	,018
	Based on trimmed mean	4,269	2	75	,018

Table 4. Tests of Homogeneity of Variances for Force Reproduction, internal rotation methods.

Tests of Normality

	AwaAD	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	DF	Sig.	Statistic	DF	Sig.
Away	A0	,142	26	,193	,920	26	,044
	A45	,086	26	,200*	,972	26	,664
	A80	,210	26	,005	,780	26	,000

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Table 5. Tests of Normality for Force Reproduction, external rotation methods.

Test of Homogeneity of Variance

		Levene Statistic	df1	df2	Sig.
Away	Based on Mean	,028	2	75	,973
	Based on Median	,081	2	75	,922
	Based on Median and with adjusted df	,081	2	59,768	,922
	Based on trimmed mean	,043	2	75	,958

Table 6. Tests of Homogeneity of Variances for Force Reproduction, external rotation methods.

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	DF	Sig.	Statistic	DF	Sig.
EB	,205	12	,175	,873	12	,072
Std	,207	12	,166	,870	12	,066
Math	,206	12	,172	,875	12	,076
FilterMath	,206	12	,170	,875	12	,077

a. Lilliefors Significance Correction

Table 7. Tests of Normality for all the onset processing methods.

Test of Homogeneity of Variances

Onset

Levene Statistic	df1	df2	Sig.
,004	3	44	1,000

Table 8. Test of Homogeneity of Variances for all the onset processing methods.

Tests of Normality

	timemethod	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	DF	Sig.	Statistic	DF	Sig.
timeonset	1,00	,208	12	,162	,875	12	,076
	2,00	,208	12	,161	,875	12	,075
	3,00	,203	12	,184	,876	12	,078
	4,00	,203	12	,183	,874	12	,074

a. Lilliefors Significance Correction

Table 9. Normality tests for the time criteria.

Test of Homogeneity of Variance

		Levene Statistic	df1	df2	Sig.
timeonset	Based on Mean	,000	3	44	1,000
	Based on Median	,000	3	44	1,000
	Based on Median and with adjusted df	,000	3	44,000	1,000
	Based on trimmed mean	,000	3	44	1,000

Table 10. Homogeneity test of variance for the time criteria

Tests of Normality

	Trial	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	DF	Sig.	Statistic	DF	Sig.
B	1,00	,212	14	,089	,942	14	,450
	2,00	,234	14	,036	,851	14	,023
	3,00	,188	14	,193	,842	14	,017
DA	1,00	,097	14	,200*	,976	14	,944
	2,00	,187	14	,200*	,853	14	,024
	3,00	,133	14	,200*	,982	14	,983

DM	1,00	,259	14	,011	,804	14	,006
	2,00	,171	14	,200*	,880	14	,059
	3,00	,207	14	,107	,880	14	,059
DP	1,00	,239	14	,029	,842	14	,017
	2,00	,164	14	,200*	,884	14	,065
	3,00	,217	14	,074	,827	14	,011
GD	1,00	,234	14	,037	,866	14	,037
	2,00	,122	14	,200*	,967	14	,838
	3,00	,196	14	,152	,860	14	,030
Ip	1,00	,137	14	,200*	,938	14	,389
	2,00	,210	14	,095	,947	14	,517
	3,00	,282	14	,004	,698	14	,000
LTT	1,00	,259	14	,012	,844	14	,019
	2,00	,144	14	,200*	,921	14	,229
	3,00	,301	14	,001	,710	14	,000
PC	1,00	,137	14	,200*	,912	14	,169
	2,00	,259	14	,012	,823	14	,010
	3,00	,210	14	,096	,867	14	,038
PE	1,00	,257	14	,012	,826	14	,011
	2,00	,247	14	,021	,914	14	,178
	3,00	,236	14	,033	,843	14	,018
RM	1,00	,171	14	,200*	,950	14	,554
	2,00	,202	14	,127	,844	14	,018
	3,00	,243	14	,024	,843	14	,018
Serr	1,00	,183	14	,200*	,921	14	,231
	2,00	,237	14	,032	,899	14	,109
	3,00	,171	14	,200*	,937	14	,386
Sp	1,00	,091	14	,200*	,977	14	,950
	2,00	,227	14	,048	,875	14	,050
	3,00	,201	14	,132	,869	14	,041
UT	1,00	,144	14	,200*	,964	14	,792
	2,00	,162	14	,200*	,932	14	,323
	3,00	,395	14	,000	,523	14	,000

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Table 11. Normality tests for the EMG ABD work

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.

B	,235	2	39	,792
DA	,926	2	39	,405
DM	1,142	2	39	,330
DP	1,151	2	39	,327
GD	,116	2	39	,890
Ip	,374	2	39	,690
LTT	4,252	2	39	,021
PC	,780	2	39	,465
PE	,375	2	39	,689
RM	1,802	2	39	,178
Serr	,536	2	39	,589
Sp	,071	2	39	,932
UT	2,276	2	39	,116

Table 12. Homogeneity test of variance for the Abduction work

Tests of Normality

	Trial	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
B	1,00	,115	14	,200*	,971	14	,884
	2,00	,277	14	,005	,863	14	,033
	3,00	,150	14	,200*	,961	14	,736
DA	1,00	,127	14	,200*	,961	14	,747
	2,00	,166	14	,200*	,969	14	,868
	3,00	,208	14	,102	,833	14	,013
DM	1,00	,196	14	,149	,885	14	,069
	2,00	,240	14	,028	,879	14	,057
	3,00	,209	14	,099	,826	14	,011
DP	1,00	,184	14	,200*	,957	14	,671
	2,00	,230	14	,044	,841	14	,017
	3,00	,118	14	,200*	,981	14	,978
GD	1,00	,146	14	,200*	,921	14	,228
	2,00	,183	14	,200*	,947	14	,510
	3,00	,131	14	,200*	,903	14	,125
Ip	1,00	,187	14	,200*	,904	14	,129
	2,00	,189	14	,191	,900	14	,114
	3,00	,133	14	,200*	,969	14	,858
LTT	1,00	,117	14	,200*	,982	14	,985
	2,00	,179	14	,200*	,944	14	,478
	3,00	,141	14	,200*	,963	14	,775
PC	1,00	,411	14	,000	,497	14	,000

	2,00	,212	14	,089	,855	14	,026
	3,00	,226	14	,052	,773	14	,002
PE	1,00	,289	14	,002	,570	14	,000
	2,00	,155	14	,200*	,890	14	,082
	3,00	,142	14	,200*	,965	14	,799
RM	1,00	,162	14	,200*	,968	14	,850
	2,00	,113	14	,200*	,971	14	,885
	3,00	,182	14	,200*	,917	14	,201
Serr	1,00	,181	14	,200*	,897	14	,102
	2,00	,210	14	,093	,836	14	,015
	3,00	,149	14	,200*	,971	14	,884
Sp	1,00	,235	14	,034	,801	14	,005
	2,00	,195	14	,154	,961	14	,732
	3,00	,178	14	,200*	,879	14	,056
UT	1,00	,157	14	,200*	,935	14	,358
	2,00	,157	14	,200*	,924	14	,250
	3,00	,153	14	,200*	,935	14	,356

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Table 13. Normality tests for the EMG volleyball task work

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
B	,427	2	39	,655
DA	1,540	2	39	,227
DM	,787	2	39	,462
DP	,270	2	39	,765
GD	,846	2	39	,437
Ip	1,029	2	39	,367
LTT	,593	2	39	,558
PC	,738	2	39	,485
PE	1,199	2	39	,312
RM	1,692	2	39	,197
Serr	,547	2	39	,583
Sp	1,825	2	39	,175
UT	,813	2	39	,451

Table 14. Homogeneity test of variance for the EMG volleyball study

APPENDIX 7 – MEASUREMENT AND MEASUREMENT ERRORS

Reliability studies of assessment tools in rehabilitation enable the investigator to be sure that the instrument detects the actual changes in what is being measured and not the errors (Rankin and Stokes, 1998).

Minimal error during collection of data is critically important to all research (Atkinson and Nevill, 1998) in order to enable identification of changes, but research measurements are always prone to errors, which may lead to differences between the measured value and the true value (Bartlett and Frost, 2008, Hopkins, 2000). The true value component is theoretically the average score of a subject recorded from an infinite number of trials. The error component is the difference between the observed score and the true score (Vincent and Weir, 2012).

These errors have a major impact on attempts to measure changes between repeated measurements (Hopkins, 2000). Studying the reliability of a measure is a matter of repeating the measurement a reasonable number of times on a reasonable number of individuals (Hopkins, 2000). Although reliability depends on the population in which measurements are made (Bartlett and Frost, 2008), some authors report it as a characteristic that describes how good a device really is. Experience tends to show the importance of the user, since education, training, health status, environment, and motivation, all can influence the outcome and introduce variability in the system (Fries, 2013). Under these assumptions, sources of error include errors due to biological variability, instrumentation, error by the subject, and error by the tester (Weir, 2005).

Thus there are many ways in which measurement error occurs. At the simplest level, can break measurement error down into two broad categories: random error (noise) and systematic error (e.g. learning effect) (Vincent and Weir, 2012).

Reliability refers to the consistency of a test score or measurement (Weir, 2005) and is linked to specific types of consistency such as (a) consistency of results over time; (b) consistency of results between different examiners and (c) consistency of results with different testing conditions, including with different patients (Amin and Khoo, 2009).

Vincent and Weir describes reliability in terms of reproducibility and consistency including test-retest reliability (1), inter-rater reliability (2) and intrarater reliability (3). Test-retest reliability is a test that is administered to a sample and repeated at least once.

The measurement derived from the tests are then compared to each other. In interrater reliability different raters give a value or rate to a measurement to the same subject which are compared. Intrarater reliability assesses the ability of a given rater to give similar scores (Vincent and Weir, 2012).

According to Bartlett and Frost (Bartlett and Frost, 2008), reliability relates the magnitude of the measurement error between participants. If reliability is high, measurement errors are small in comparison to the true differences between participants, so that participants can be relatively well distinguished. The reliability parameter is also known as an intraclass correlation (ICC) (Capranica et al., 1992, Bartlett and Frost, 2008, Weir, 2005). Reliability takes values between zero and one, with a value of one corresponding to zero measurement error and a value of zero meaning that all the variability in measurements is due to measurement error. The reliability of a measurement method is often of interest when measurements are to be used to differentiate between participants or groups of participants (Bartlett and Frost, 2008).

The intra-class correlation coefficient avoids problems of reversing the order of the measurements when several repeated measures are undertaken, because it estimates the average correlation among all possible orderings of pair. It also extends easily to the case of more than two observations per subject, where it estimates the average correlation between all possible pairs of observations (Bland and Altman, 1996c). When dealing with intraobserver variation using the same method of measurement, where the repeated observations are made by the same observer on the same subject, there should not be any consistent bias, and then it is advised to use the ICC. Correlation is only inappropriate for the study of agreement between different methods of measurement (Bland and Altman, 2003).

According to Bland and Altman (1990) the intraclass correlation coefficient can be used, for example, as an index of correlation between repeated measures by the same method, i.e. as an index of repeatability.

Repeatability refers to the variation in repeat measurements made on the same subject under identical conditions. Constants are the instrument or method and the observer, over a short period of time (Bartlett and Frost, 2008).

According to The International Standards Organization (ISO:5725, 1994), repeatability refers to test conditions that are as constant as possible, where independent test results are obtained with the same method on identical test items in the same laboratory by the same operator, using the same equipment within “short” intervals of time. Whereas reproducibility refers to test conditions under which results are obtained with the same method on “identical” test items, but in different laboratories with different operators and using different equipment.

One way to describe the measurement error is the within-subject standard deviation and an alternative is to report the repeatability coefficient as described by Bland and Altman (1996b). According to the above mentioned authors, after averaging the variances (the square of the standard deviations), the squared route of the obtained value is used to estimate the within-subject standard deviation (δ_w) For this calculation to be valid the standard deviation should be unrelated to the magnitude of the measurement (Bland and Altman, 1996d, Bland and Altman, 1996b). The measurement error can be quoted as $2.77\delta_w$, the difference between a subject’s measurement and the true value which would be expected to be less than $1.96\delta_w$ for 95% of the observations (confidence interval). Under the above mentioned assumptions, the repeatability is calculated using the formula $\sqrt{2}x1.96x\delta_w$. So the difference between two measurements for the same subject is expected to be less than $2.77\delta_w$ for 95% of pair of observations (Bland and Altman, 1996b).

Whereas agreement between repeat measurements is a characteristic of the method or instrument, reliability depends on both the magnitude of measurement errors and the true heterogeneity in the population in which measurements are made (Bartlett and Frost, 2008).

According to Hopkins (Hopkins, 2000), reliability is a measure of within-subject variation, change in the mean, and retest correlation. For the author, the within-subject variation is the most important type of reliability measure for researchers, since it affects the precision of estimates of change in the variable of an experimental study. The statistic that relates to this notion is the standard deviation of the individual’s values.

Since the general form of the ICC is a ratio of variance due to differences between participants to the total variability in the data, the ICC is reflective of the ability of a test to differentiate between different individuals. This means that the relationship between between-participants variability and the magnitude of the ICC has been used as a criticism of the ICC (Weir, 2005). Samples containing participants who differ greatly will produce larger correlation coefficients than will samples containing similar participants (Bland and Altman, 1996c). This way, methods based on correlation coefficients have been described as “relative reliability methods” and researchers should be cautious in concluding acceptable relative reliability even if a correlation is above 0.9 (Atkinson and Nevill, 1998).

To avoid this problem, this index of relative reliability should be accompanied by an absolute reliability index like the SEM (Standard Error of measurement) (Weir, 2005). Hopkins refers to the SEM as the “typical error” (Hopkins, 2000), a measure of precision. The SEM has the same units as the measurement of interest, whereas the ICC is unit less (Weir, 2005). According to the same author $SEM = SD\sqrt{1 - ICC}$, where SD is the standard deviation of the scores from all participants in the sample.

The standard error of the measurement is a measure of discrepancy (error) between repeated scores. It represents the extent of error associated with retesting. The confidence interval of the measurement represents the smallest difference attributable to status change, as distinct from measurement error (95% probability)(Hayes et al., 2001).

The SEM is an index that can be used to define the difference needed between separate measures on a subject for the difference in the measures to be considered real. The SEM can be used to determine the minimum difference (MD) to be considered “real” and can be calculated as follows (Weir, 2005):

$$MD = SEMx1.96x\sqrt{2}$$

Once the MD is calculated, then any change in a subject’s score, either above or below the previous score, greater than the MD is considered real.

Analysis of variation for the detection of systematic bias (ANOVA with repeated measures, with sphericity correction) can be used, however, the sole use of ANOVA is not enough since detection of systematic bias is affected by large random (residual) variation (Atkinson and Nevill, 1998).

Summing up, the main components of measurement error are systematic bias (learning and fatigue effects on the tests) and random error due to biological or mechanical variation (Atkinson and Nevill, 1998).