How does a bout of repeated spiking affect shoulder muscle activity during a rapid arm raise task? A study of trained male volleyball players.

William White

A thesis submitted in partial fulfilment

of the requirements for the degree of

Master of Science

at the University of Otago, Dunedin,

New Zealand.

2022

Abstract

There is a high prevalence of overuse injuries in volleyball, which can result in participation time loss. The game of volleyball involves repetitive overhead movements such as serving and spiking. Overhead motions rely on effective movement of the scapula, produced by the shoulder muscles. Muscle fatigue may affect scapula thoracic (ST) muscle function, and in turn affect scapula kinematics. Overuse injuries, such as subacromial impingement syndrome (SIS), have been linked to dysfunctional scapula kinematics and ST muscle activity among overhead athletes. The causal nature of this link is unclear, that is, does injury lead to altered kinematics and muscle function, or vice versa? If injury arises due to dysfunctional scapula control, then states of fatigue could increase the risk of injury by causing changes in muscle function.

The aim of this study was to investigate the effect of fatigue, caused by the repetitive overhead action of hitting (spiking) in volleyball, on shoulder muscle activation. Surface electromyography (EMG) was used on ST muscles to evaluate peak amplitude, time to peak, frequency, and area under the EMG curve. Thirteen trained healthy volleyball players were tested before and after a repetitive spiking intervention in a controlled laboratory setting.

In the post-intervention measurement compared to the pre, a reduction in peak amplitude ($p < 0.05$) and area under the EMG curve ($p < 0.05$) was observed in the Anterior Deltoid (AD). Lower Trapezius (LT) was found to have increased area under the curve ($p < 0.01$), increased frequency ($p < 0.01$), and decreased time to peak ($p < 0.05$). A decreased time to peak was also observed for the MT ($p < 0.01$).

The results indicate that the spiking intervention does affect the scapulothoracic muscle activation. An explanation for these results is that the system acts to maintain stability of the shoulder girdle during rapid tasks, through anticipatory postural adjustments in the scapulothoracic muscles. These changes in muscle activation were observed in healthy participants, which suggests that muscle dysfunction is a precursor to the development of injury, as opposed to a result of it.

Acknowledgements

First and foremost, the biggest thank you goes to my supervisor, Associate Professor Melanie Bussey. This Masters has been a long journey, and one that definitely needed guidance (and lots of editing) along the way – patience sure is a virtue!

A sincere thanks also goes to the staff within the department and wider Univeristy for their support. Particularly to the technician team for asssistance whenever it was much-needed, be it equipment difficulties, or simply accomodating lab time. I must also acknowledge Jill Haszard from the Biostatistics Centre for her expertise, and help in the analysis of my data.

I wouldn't have been able to do this without the willing help of my friends and teammates from the Scorps Volleyball Club and wider volleyball community in Dunedin, so thank you. I'm glad I could count on you lads to come and hit some balls around in the name of science!

To my friends, family and anyone else who has helped and encouraged me over the years - it was much needed at times and you are all very much appreciated.

Finally, to Olivia, who has without a doubt been my biggest supporter, and for whom I am eternally thankful.

Contents

List of Tables

List of Figures

1 Introduction

Volleyball is a sport in which shoulder overuse injuries are common, reported to have a 19% prevalence (Seminati & Minetti, 2013), and an incidence rate of 3 injuries per 1000 playing hours (Wang & Cochrane, 2001a). In a sport where attacking efficiency is a key performance indicator of team success (Eom & Schutz, 1992), the most common and effective form of attack hit is the spike. Therefore, players typically perform the spike action at high frequency in both training and match scenarios, (Kugler, Krüger-Franke, Reininger, Trouillier, & Rosemeyer, 1996).

Unsurprisingly, a high number of ball contacts is associated with shoulder pain presence among volleyball athletes (Frisch et al., 2017). As ball contacts accumulate over a period of playing time it follows that playing-time (i.e., exposure) is an established risk factor for shoulder overuse injuries in volleyball (Kennedy, 1980). Overuse injuries are associated with cumulative trauma as a result of pathological overloading of particular tissue structures (Leadbetter, 1992). The mechanism for pathological overloading has been defined as a trifecta of excessive mechanical loading, insufficient recovery time and potential unpreparedness of the athlete for the load (Windt & Gabbett, 2017). This knowledge has led to some sports implementing guidelines in order to reduce the risk of injury, such as the pitch count restriction in baseball, however no such restrictions or recommendations are in place for volleyball. Playing time and number of contacts are risk factors for injury in volleyball, however it is unclear as to the exact mechanisms. That is, the exact contribution of these factors on the mechanism of injury are not understood.

The most common shoulder overuse injury in overhead sports is subacromial impingement syndrome (SIS) (Edwards, Bell, & Bigliani, 2009). The presentation of SIS can differ according to the severity of the condition. Impingement syndrome begins with mild discomfort that may progress to light pain during overhead motion, then to severe pain that can prohibit athletic endeavours. More serious impingement is often acompanied by increased weakness and insufficient range of motion in shoudler abduction and external rotation (Kennedy, 1980). Overhead athletes rely heavily on effective scapula movement to facilitate shoulder range of motion. Scapula motion is controlled through synergynistic action of multiple muscles around the shoulder. It has been posed that repetitive overhead actions can alter muscle function and affect scapula kinematics during movement (Bradley &

Tibone, 1991; McQuade, Dawson, & Smidt, 1998; McQuade, Wei, & Smidt, 1995). Research has also established that dysfunctional scapula motion and altered muscle function is observed in patients with SIS (Cools, Cambier & Witvrouw, 2008; Cools, Witvrouw, De Clercq, Danneels, & Cambier, 2003). The causal nature of this link is unclear, that is, does injury lead to altered kinematics and muscle function, or vice versa? If injury arises due to dysfunctional scapula control, then states of fatigue could increase the risk of injury by causing changes in muscle function.

Since the mechanical work done by a muscle is influenced by both the time it is active for, and on the level of activation within the muscle, it follows that changes in temporal measures could be accompanied by changes in muscle activation amplitude and frequency. Changes in muscle timing and activation may impact scapula control (ability to sense and manipulate the position of the scapula). It has been hypothesised that delayed and reduced activation of scapula stabilisers are the mechanism responsible for causing SIS in overhead athletes (Ludewig & Cook, 2000).

Significance of the study

Changes in muscle activation amplitude, frequency and timing have been observed in injured overhead athletes. The literature is currently unclear as to whether altered muscle behaviour is a causal factor for injury, or a result of it. Changes in muscle activation amplitude, frequency and timing have also been associated with muscoloskeletal fatigue, leading to the hypothesis that fatigue may be a precursor to injury in overhead athletes. Literature has begun to explore this hypothesis, however no authors have exclusively looked at the effect of fatigue caused by repetitive spiking in volleyball players.

Therefore, in this study, the effect of fatigue, caused by a bout of repetitive spiking, on the aforementioned muscle outcomes of amateur volleyball players will be quantified. The results may find any of the following significant results: delay in muscle peak amplitude timing, increase in EMG amplitude, or decreased firing frequency when in a state of fatigue. Findings to the contrary are also possible. In the former instance, training for these athletes should be designed to increase the fatigue resistance of the muscles, so that the fatigue-induced changes have less effect, potentially lessening the risk of injury.

Research questions

The following research questions will be addressed in the thesis:

1. What effect does a repeat bout of volleyball spiking have on the scapulothoracic muscles peak amplitude timing in trained volleyball players?
2. What effect does a repeat bout of volleyball spiking have on the scapulothoracic muscles median frequency in trained volleyball players?
3. What effect does a repeat bout of volleyball spiking have on measures of scapulothoracic muscles EMG amplitude in trained volleyball players?

Operational definitions of terms

i) Attack (or attack hit) – refers to the contact of a volleyball team which sends the ball over the net and into the opposing teams playing space.

ii) Spike – refers to the most commonly seen type of contact used for the attack hit. A spike is a dynamic action used to direct the ball downwards at high velocity, in an attempt to prevent the opposition from returning the ball.

iii) Overuse injury – an injury defined as being "associated with cumulative trauma as a result of pathological overloading of particular tissue structures" (Leadbetter, 1992).

iv) Scapulohumeral rhythm - defined as how the scapula and humerus move relative to one another (McQuade et al., 1998)

v) Muscle onset – the earliest time at which a muscle becomes active, based on a given normalised root mean squared (RMS) signal increase from it's baseline.

vi) Muscle peak amplitude – the time at which a muscle displays it's maximum normalised RMS value during a movement cycle

vii) Order of onset – the order of onset within a group of muscles, ranked from earliest onset to latest.

viii) Peak order – the order at which muscle peak amplitudes occur, ranked from earliest to latest.

ix) Time broadness – the time elapsed between the first muscle and last muscle's peak amplitude during a movement, relative to the total time taken to perform the movement.

x) Muscle frequency – the rate of action potentials delivered to muscle fibres. Greater frequencies usually result in summation of electrical acitivity, hence greater contractile force (Purves, 2001).

xi) Muscle amplitude – the absolute value of the normalised RMS EMG activity.

xii) Area under EMG curve – the value of the area contained between the normalised RMS signal and the zero axis, during the movement cycle. Also known as integrated EMG (iEMG).

2 Literature Review

This review of literature is comprised of four main sections. The first section reviews spiking motion used in the volleyball attack, explains it's importance, and discusses the biomechanics involved. This section also reviews potential factors that could contribute to injury, including high frequency, and large loads placed on the tissues around the shoulder. The second section reviews aetiology of shoulder injuries. Injury mechanisms and injury risk factors for key shoulder injuries are also reviewed. Thirdly, muscular fatigue will be reviewed. How fatigue affects shoulder motion is explained in this section. The final section continues to explore the effects of fatigue on muscle activity outcomes.

Before an investigation into the mechanisms and casual factors of fatigue and related injuries can be undertaken, one must first have an appreciation for the biomechanical and contextual significance of the spike.

2.1 Biomechanics of the volleyball spike

The spike in volleyball is a dynamic overhead motion that is performed frequently, at high velocity, and with large forces involved. It is the most common method of attack and is an essential part of the game, since greater attacking success is correlated with a higher probability of winning (Eom & Schutz, 1992). The spike has often been compared to various other throwing-like sporting actions, including in baseball, American football, handball, water-polo, and even tennis serving, due to the joint actions involved and the high-velocity nature in which they are performed (Escamilla & Andrews, 2009). It is the most stressful overhead activity in the game, exposing the athlete to a greater amount of force and torque when compared to the serve (Reeser, Fleisig, Bolt, & Ruan, 2010). The kinematics of the spike have recently been the subject of a systematic review (Oliveira, Moura, Rodacki, Tilp, & Okazaki, 2020) providing insight into the demands of the movement. A thorough description of these demands are reviewed in this chapter.

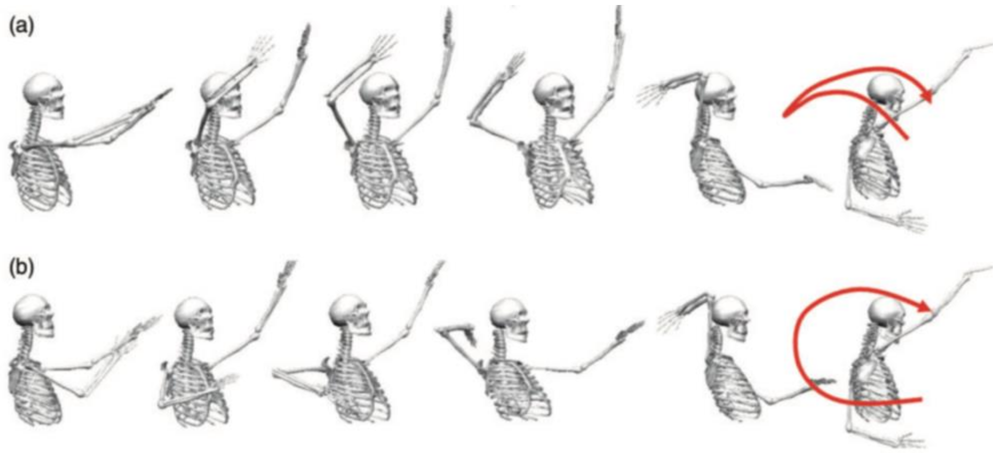


Figure 1. Illustration of the two arm swing techniques in the volleyball spike: a) 'elevation style' (traditional), and b) 'backswing style' (alternative), from Oliveira et al, 2020

Two main styles of arm swing have been identified in the literature, and are depicted in Figure 1. The two techniques can be segmented by the same phases, with the primary difference between these two styles being the degree of arm elevation achieved in the wind up and cocking phases. Research has indicated minimal differences between the two types of arm swing, with the alternative technique providing slightly greater ball velocities and segment rotation velocities (Seminati, Marzari, Vacondio, & Minetti, 2015). The attack manoeuvre begins with a wind up phase (Escamilla & Andrews, 2009). In this phase the arm moves from an extended and abducted position and undergoes shoulder flexion to finish in an overhead position. The next phases of the movement are cocking, from the initiation of shoulder external rotation

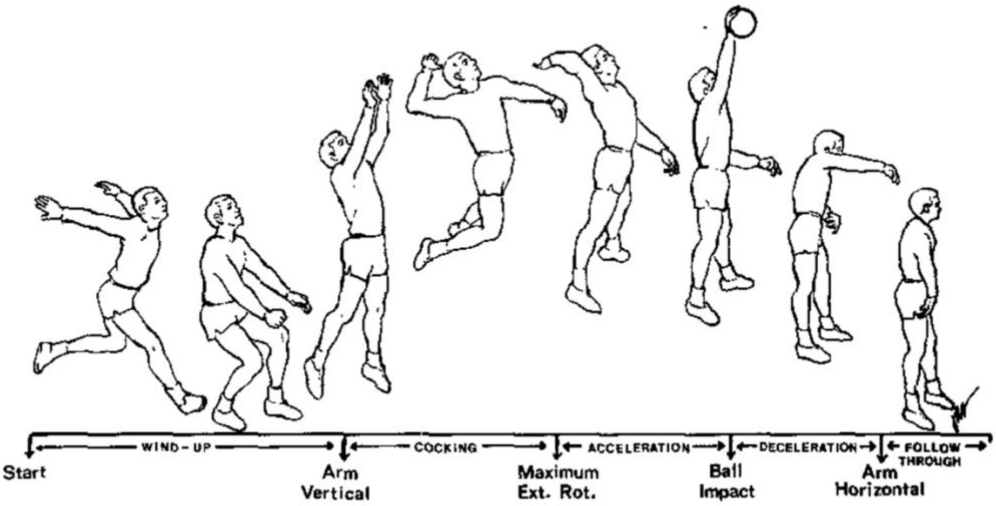


Figure 2. The five phases of the volleyball spike, from Rokito et al, 1998

to maximal shoulder external rotation; acceleration, from maximum external rotation to ball impact; deceleration, from ball impact to when the arm is perpendicular to the trunk; and follow through, from the perpendicular arm to the end of the arm motion. Further variation in the spike can arise according to the direction of the shot in relation to the hitting shoulder. The two primary shots are: the straight shot, in which the follow through is more directed to the ipsilateral hip; and the cross-court, or cross-body shot, in which the follow through is directed to the contralateral hip. According to researchers, no significant kinematic differences exist between the two shots (Mitchinson, Campbell, Oldmeadow, Gibson & Hopper, 2013; Reeser, Fleisig, Bolt & Ruan, 2010).

Reeser et al, (2010) quantified the demands of the volleyball spike in female Division 1 collegiate players. Results found that subjects experienced around 40 N·m of torque at the moment of maximum external rotation, forces of roughly 400 N during arm acceleration, and angular internal rotation velocities of around 2500 degrees per second. In addition to these findings, it has been documented that elite players attack with greater ball velocity. In a study comparing professional players from the Belgian league to players in a youth academy, spike velocity was found to be higher in the former group than the latter, and in males compared to females, at both levels (Serrien, Ooijen, Goossens, & Baeyens, 2016). The data reported by Reeser et al (2010) may be an underestimation of the demands experienced by both professional female players, and males at various levels. It is estimated that elite volleyball players may perform the spike up to 40,000 times in a year (Kugler et al., 1996). This high frequency combined with large forces, torques and velocities places large amounts of stress on the shoulder.

Many muscles contribute to the spiking action. In the wind up phase, athletes rely heavily on anterior deltoid, infraspinatus and supraspinatus to raise the arm and stabilize the head of the humerus (Rokito, Jobe, Pink, Perry, & Brault, 1998). High activity levels from the scapulothoracic muscles are also likely during this phase, although this has not been quantified in research. This is due to the requirement to stabilise the scapula during arm elevation

(Edwards et al., 2009). Shoulder internal rotation strength is a key performance indicator in volleyball attacking (Forthomme, Croisier, Ciccarone, Crielaard, & Cloes, 2005; Wang & Cochrane, 2001b), and as such, the rotator cuff muscles play a significant role throughout all phases of the attack. An exception is during the follow through, in which the musculature is active at low levels (Rokito et al., 1998). Athletes, coaches and trainers aim to improve internal rotation strength to bring greater success, however training the shoulders needs to be approached in an informed and structured manner, so as to avoid injury. A heavy training emphasis on internal rotation can lead to the anterior aspect of the joint becoming stronger than the posterior aspect, the implications of which are elaborated on in the next chapter.

The evidence in this review has given insight in to the demands of the attacking motion. There exists a handful of subtle differences in the performance of the spike, but for the most part the kinematics involved with all techniques are similar. These demands include high measures of force, torque, and velocity, which performed repetitively place large stress on the shoulder and scapulothoracic joints. In addition, a key performance indicator has been identified in shoulder internal rotation strength. This is particularly noteworthy when considering mechanisms of injury, around which a discussion ensues in the following section.

2.2 Shoulder overuse injuries

Repetitive performance of the spike in volleyball can lead to shoulder injury. Because of the demands the spike places on the shoulder joint, morphological adaptations can arise and contribute to overuse injuries. This chapter discusses the prevalence, incidence and severity of these injuries, as well as highlighting those most common. Risk factors and mechanisms for these pathologies are also introduced.

Overuse injuries are defined as being *"associated with cumulative trauma as a result of pathological overloading of particular tissue structures,"* (Leadbetter, 1992). There are numerous ailments affecting the shoulder that fall into the category of overuse injuries. Of these injuries, subacromial impingement syndrome (SIS) and subscapular neuropathy are most commonly reported in literature (Seminati & Minetti, 2013). Joint instability, tendinitis and muscle strains were the next most common, however only occur approximately 50% as often as the aforementioned. Of the two most commonly reported shoulder overuse injuries, subscapular neuropathy is most prevalent in elite athletes, with this demographic accounting for over half of these types of injuries reported in literature (Seminati & Minetti, 2013). Conversely, impingement is far more common in amateur/recreational players, with this demographic accouting for over half of the reports of this condition. Moreover, there will naturally be a far greater proportion of volleyball athletes at the amateur level than the elite. If research is to improve health outcomes for the majority of volleyball players, focusing on understanding subacromial impingement should be a priority.

Volleyball has a high prevalence of shoulder injuries, reported at 25% by Escamilla & Andrews (2009) and 29% by Bhat & Balamurugan (2017). Shoulder overuse injuries specifically are reported to have a prevalence of 19% in volleyball players (Seminati & Minetti, 2013). An incidence rate for shoulder overuse injuries of 3.0 per 1000 playing hours has also been reported (Wang & Cochrane, 2001a). Moreover, this data is likely to be underestimated due to the tendency of players to fail to report chronic injuries (Jacobson & Benson, 2001). Research has found that the mean duration of time away from volleyball competition due to shoulder overuse injuries was 6.2 ± 9.4 weeks (Verhagen, Van Der Beek, Bouter, Bahr, & Mechelen, 2004). This figure is comparable to the mean duration of time lost to shoulder injuries in Major League Baseball, between 38 - 71 days per season (Li et al., 2013) (Fares et al., 2020).

Research on risk factors associated with shoulder overuse injury in volleyball players is scarce. Only one review was found in the literature, which identified number of hours played, limited shoulder internal rotation mobility, and internal/external rotation muscular imbalance as risk factors

(Seminati & Minetti, 2013). This is particularly significant due to the importance of internal rotation as discussed in the previous section. Awareness of these risk factors is valuable for players, coaches and physical therapists, however the specific mechanisms for the factors causing overuse injuries are unclear. Another review (Kilic, Maas, Verhagen, Zwerver, & Gouttebarge, 2017) examined all volleyball injuries and concluded, in agreement with Seminati & Minetti (2013), that risk factors for shoulder overuse injuries require further investigation.

2.2.1 Subacromial impingement syndrome

The most common shoulder pathology across all athletes is SIS (Edwards, Bell, & Bigliani, 2009), also referred to as classic or external impingement. It is also the shoulder pathology and in volleyball athletes specifically (Seminati & Minetti, 2013). The cause of this condition is accumulation of microtrauma to shoulder structures that lie inferiorly to the acromion, such as bursa and the tendons of the rotator cuff muscles. This occurs when the subacromial space is not sufficient to accomodate these structures, which can be a result of the structures themselves becoming inflamed, or by a physical reduction in the subacromial space – which occurs with protraction and anterior tilting of the scapula. This can arise due to an inability to stabilise the scapula, which is required during arm elevation, particularly in the range of 70-120 degrees (Edwards, Bell, & Bigliani, 2009). The risk for impingement is greater the more often the scapula is put in this position, as affirmed by pioneering researchers on the subject (Kennedy, 1980). The high frequency of overhead actions required in volleyball, puts athletes at heightened risk of shoulder impingement injury. There is evidence to support this in the literature, with a higher number of ball contacts being linked to greater shoulder pain in young volleyball athletes (Frisch et al., 2017). Moreover, the risk factors for pain identified in the literature align with the mechanisms of SIS. The importance of internal rotation strength for spiking success means that athletes often have dominant internal rotators (Challoumas, Stavrou, & Dimitrakakis, 2017; Seminati & Minetti, 2013). This anterior imbalance may also contribute to impingement during elevation, a concept that is discussed further in section 2.2.2. Other mechanisms for SIS have also been proposed in research, such as anterior hyperlaxity of the glenohumeral capsule (Challoumas et al., 2017), glenohumeral internal rotation deficit (GIRD), and glenohumeral external rotation gain (Reeser et al., 2010; Cools, Johansson, Borms & Maenhout, 2015), with the latter two mechanisms often accompanying the former.

2.2.2 Scapula control in overhead motion

Scapula motion is complex due to its anatomical position and lack of bony attachments, which means it relies on the surrounding musculature to achieve stability during movement. Anterior tilting can arise from weakness of the dorsal muscles (which are responsible for posterior scapular tilting) and/or tightness of pectoralis minor (which is responsible for the anterior tilting) particularly (Castelein, Cagnie, Parlevliet, Danneels, & Cools, 2015). Multiple researchers have established that muscular fatigue has a significant effect on scapula kinematics, and as a result, scapulohumeral rhythm (Bradley & Tibone, 1991; McQuade et al., 1998; McQuade et al., 1995).

Scapulohumeral rhythm is the ratio of scapula movement to glenohumeral movement during arm motion. In 90 degrees of arm movement, the scapula's elevation is said to contribute 30 degrees of this range (Inman, Saunders & Abbot, 1994). The muscles responsible for producing scapula movement are the fibres of the trapezius, coupled with the serratus anterior and rhomboids (Kibler, 1998). If these muscles are unable to produce movement of the scapula, it will not elevate during arm motion, the consequences of which will be explored more deeply further on in this review. Changes in the scapulohumeral rhythm may have implications for injury to volleyball athletes when considering the large forces experienced in the spiking action.

In conclusion, it is clear that shoulder overuse injuries are commonplace in volleyball, and tend to keep athletes away from the court for significant periods of time. Of these injuries, SIS is the most prevalent, which is unsurprising considering the repetitive nature, and demands of spiking - with great need for scapula stabilisation during overhead movement, coupled with internal rotation dominance. Stabilization is achieved through coordination of the scapulothoracic musculature, however this may be affected with the accumulation of fatigue during sports participation. The specific ways that muscle function changes with fatigue are discussed in detail in the following chapters.

2.3 Fatigue

It is important to note that this section (and relevant subsections) on fatigue are a very brief summary of aspects that are most applicable to the research at hand. It is acknowledged that there are many other processes that contribute to fatigue. Whilst these are important to understand, they are physiological in nature, and as this thesis will maintain a biomechanical perspective, a discussion of these physiological pathways is beyond the scope of this review.

2.3.1 Skeletal muscle fatigue

Enoka and Duchateau define muscular fatigue as *"a decrease in the maximal force or power that the involved muscles can produce, and it develops gradually soon after the onset of the sustained physical activity"* (Enoka & Duchateau, 2008). This fatigue occurs when tasks are performed with large and sustained forces in high power short-duration repetitive contractions, or when a task requires low power sustained single or repetitive contractions (Faulkner, Brooks, & Zerba, 1995). The example of a volleyball player performing multiple attack hits during a match or training fits the former description. It is well understood that the generation of muscular force is a process involving many components. The reasons why fatigue causes a decrease in force output are numerous and are not as well understood. The next sections in this chapter consider various factors that contribute to this outcome.

2.3.2 Central fatigue

Central fatigue refers to musculoskeletal fatigue that is developed due to a failure of the central nervous system (CNS) to drive the motor neurons adequately (Gandevia, 2001). The CNS is constituted of the brain and its spinal pathways, and is responsible for controlling human movement. The mechanisms of central fatigue serve to dampen the output of the CNS. These mechanisms are numerous, including: a decrease in MN excitability that comes with repetitive firing, an increase in inhibitory feedback from muscle afferents, and a reduction in excitatory drive from the muscle spindles (Taylor, Amann, Duchateau, Meeusen, & Rice, 2016). However, this definition only encompasses fatigue induced by maximal fatiguing tasks, which are accompanied by reductions in EMG activity. Contrastingly, fatiguing tasks that require submaximal force output generally result in greater voluntary cortical output, and subsequent increases in EMG activity (Taylor et al., 2016). This increase may occur to compensate for the decrease in responsiveness of the MN, resulting in consistent muscular output. With different fatiguing scenarios come very different physiological responses, and as such it is important for researchers and practitioners to distinguish between the two.

2.3.3 Peripheral fatigue

Peripheral fatigue is attributed to processes at or distal to the neuromuscular junction (Taylor et al, 2016). While it is likely that central and peripheral fatigue develop simultaneously, there may be a greater contribution of one type of fatigue to the overall reductions in muscle outputs observed. The contribution of each may be influenced by the nature of the fatiguing activity, a concept which is considered in greater detail in a later section of this review. Early research has shown that muscles stimulated artificially, using external electrical stimulus rather than a signal from the CNS still display signs of fatigue, implying that some fatigue processes occur peripherally (Gandevia, 2001). Peripheral mechanisms discussed commonly in literature include: 1) loss of electrical conduction from muscle membrane, 2) reduced calcium release from the sarcoplasmic reticulum (SR), 3) impaired interactions between myosin and actin during cross-bridge cycling, 4) impaired reuptake of calcium, and 5) bioenergetic failure due to impaired oxidative phosphorylation, glycolysis, or both (Davis & Walsh, 2010). With many factors at play in the development of both central and peripheral fatigue, it is unclear which type of fatigue may be more present in certain sporting actions.

2.3.4 Task specificity of fatigue

Cairns, Knicker, Thompson & Sjøgaard (2005) proposed the theory of task dependency of muscle fatigue, which outlines that muscle fatigue is not caused by a single mechanism, rather the primary cause is specific to the processes that are stressed in the fatiguing task. This means that fatigue caused by one task may not elicit the same outcomes as a different task, even if the two tasks utilise the same muscle groups. Task specificity is also relevant in that some research has suggested that certain types of tasks are more likely to elicit certain mechanisms of fatigue. For example, Yoon Schlinder, Griffith & Hunter (2007) found that low force contractions produced greater levels of central fatigue that high force contractions when performing an isometric task. The volleyball spike is a low force-high velocity movement, and as such athletes may be more susceptible to developing central rather than peripheral fatigue.

2.3.5 Fatigue affecting shoulder motion

Scapulohumeral rhythm is defined as how the scapula and humerus move relative to one another (McQuade, Dawson & Smidt, 1998). Differences in scapulohumeral rhythm can be likened to altered kinematics during movement. It has been hypothesised that repetitive overhead motion may lead to increased injury risk in overhead or throwing athletes due to fatigue (Fleisig, Andrews, Dillman, & Escamilla, 1995; Wilk, Andrews, Cain, & Devine, 2009). The fact that fatigue manifests in diminished force outputs supports the hypothesis that fatigue may play a key role in developing overuse injuries, such as SIS. A reduction in force produced by the scapulothoracic muscles may result in greater instability during overhead movements, and as a result the scapula may drift into the undesirable position of anterior tilt. If this position is produced repeatedly, it is likely that an athlete will develop pain, which in turn may affect spiking performance.

Existing evidence on fatigue development in relation to shoulder motion concludes that muscular fatigue does has a significant effect on scapular kinematics, and as a result, scapulohumeral rhythm (Bradley & Tibone, 1991; McQuade, Wei & Smidt, 1995; McQuade, Dawson & Smidt, 1998). These effects are explored in greater detail in subsequent sections of this review. The majority of aforementioned fatigue studies did not use overhead athletes, nor did the fatiguing protocols adhere to the model of task specificity. Therefore, the mechanisms of fatigue do not incorporate the concept of task dependency fatigue, and the results of these studies may not represent what happens in real sporting situations.

2.3.6 Quantifying fatigue

Fatigue can be quantified in many ways, but is commonly done so by subjective reporting of the task difficulty. One commonly used method is by using a rate of perceived exertion (RPE) scale. Localized muscle fatigue has been defined as “an acute impairment in performance which may be related to an increase in the perceived effort of the desired movement and the eventual failure to maintain the desired effort” (Chaffin, 1973). In adherence to this definition, there is strong evidence in the literature that *perceived effort* is a valid method for quantifying fatigue in overhead athletes. In a study of volleyball players, it was found that a fifteen-point RPE Borg scale was a highly reliable measurement for fatigue (Sardinha & Zebas, 1986). Studies in baseball (Erickson et al., 2016), cricket (Maunder, Kilding, & Cairns, 2017) and handball (Nuño et al., 2016) have also all established RPE as valid indicators of fatigue. Recently, a study researched fatigue in specific relation to volleyball match actions (Khal, Moore, Pryor, & Singh, 2020). The subjects performed a series of repeated game-like serves, and fatigue was quantified using RPE. This measure was also validated with EMG data, using the median power frequency (MDPF) of the EMG signal. The study showed a strong correlation (0.889) between subjective RPE using a Borg scale, and the MDPF. This supports that RPE can be used as a reliable measure in future similar work.

In summary, the literature establishes that many factors are involved in the development of fatigue. While the outcomes of fatigue may be similar, regardless of the mechanism, we must appreciate the distinction between central and peripheral origins. The main effect of fatigue is a reduction in muscle force output, which has significant implications for movement control. These effects are of particular relevance to overhead athletes, who rely heavily on musculature to stabilise the scapula during motion. Importantly, failure to do so because of muscular fatigue may contribute to injury development. Research also highlights the importance of task specificity, a concept that should be applied to future studies to ensure that their methods are ecologically valid (meaning the study accurately reflects the real world context, e.g. mimics the demands accurately), and that their results are applicable to real world scenarios. Fatigue can be quantified accurately using rate of perceived exertion (RPE), and this method has been validated in many sports, including volleyball, hence it is a legitimate method for use in future work.

2.4 Muscle activity

Having identified common injuries associated with overhead sport athletes, and their potential mechanisms with respect to fatigue, this section aims to explore how fatigue may contribute to the occurrence of these injuries. Since fatigue brings about changes in muscle activity, certain variables can be focussed on to investigate this phenomenon. These variables are commonly measured through EMG properties. In this chapter, temporal muscle variables are discussed, as well as frequencies and amplitudes, with reference to how these variables are influenced by fatigue and injury. Knowledge of these links will provide greater understanding of the behaviour of the shoulder musculature and scapula in fatigued states, and may be useful in developing training methods to minimise risk of, and rehabilitate from injury.

2.4.1 Temporal and coordination muscle outcome variables

Changes in muscular timing can be linked to various types of injury (Cools et al., 2003; Phadke, Camargo, & Ludewig, 2009). As such, assessing changes in timing and coordination during movement might be an important step in identifying potentially high-risk activities. The way in which coordination is assessed in biomechanical research differs among studies, with a range of techniques available to investigators to quantify this. A description of some of these methods is given in the following paragraphs.

Much of the present research linking injury and fatigue to temporal muscle outcomes considers onset timing –the time taken for a muscle to become active. It is clear from exploration of mechanisms in previous sections of this review, that insufficient scapula control can contribute to injury. Researchers have hypothesized that delayed or premature activation of scapulothoracic musculature could be responsible for this (Wadsworth & Bullock-Saxton, 1997). This result may arise due to compromised production and propagation of signals from the CNS. Research shows an increase in onset time of scapulothoracic muscles in fatigued athletes (Cools et al., 2002). This finding is also observed in athletes with SIS when compared to controls (Cools et al., 2003; Phadke et al., 2009). Given the established links between onset timing and fatigue, it has also been hypothesised that fatigue may affect the order of shoulder muscle activation, that is the pattern of muscle onset in relation to one another. Research on this topic is limited, with Cools et al (2015) finding consistent patterns of scapulothoracic muscle activation in fatigued and non-fatigued states, which would not support the hypothesis. Looking at onset patterns in SIS populations has also been fruitless. Multiple studies have investigated scapulothoracic muscle recruitment order in patients with SIS and have concluded that the effect of injury is unclear (Moraes, Faria, & Teixeira-Salmela, 2008; Roy, Moffet, & McFadyen, 2008; Santos, Belangero, & Almeida, 2007; Wadsworth & Bullock-Saxton, 1997). This warrants further investigation on this subject. Once again, no research has explored these outcomes in volleyball athletes specifically.

Similarly to muscle onset, time to peak is another method used to describe muscle timing. It is the time taken to reach the maximum EMG value for a given muscle. Time to peak is another useful measure of muscular timing and control because it reflects at what point a certain muscle is contributing most to the movement. For example, in two scenarios with and without an intervention, a muscle may become active at the same time, however one may stay at a lower level of activation for a longer period of time. Time to peak may be especially appropriate for stabilising muscles, especially in the instance of the scapula, where movement is not caused by a single prime mover, instead many muscles contributing at once. With multiple synergists acting – including upper, middle and lower trapezius, serratus anterior, and pec minor, synchronicity is important so that all muscles collaborate and achieve the desired movement. Research regarding the effect of fatigue on time to peak EMG is limited, with no studies able to be found that considered time to peak in the scapulothoracic musculature.

Onset and time to peak can indicate changes in one particular muscle's activity, however looking at muscles in isolation does not provide an understanding of how other muscles function in unison, thus the overall coordination during a movement. Looking at the order of muscle peaks is another tool in evaluating performance. Sequential action of segments is a commonly cited biomechanical principle that states optimal movement is produced as a result of segments being moving in a proximal to distal order. Hirashima, Kadota, Sakuri, Kudo & Ohtsuki (2002) were the first to investigate a similar concept of sequential muscle action. Hirashima et al investigated both onset timing and peak timing during overarm throwing. The results found that significant sequential onset activation was found, however not peak activation. There was an observed trend of proximal to distal muscle activation, however this sequential peak activation was not proved at a statistically significant level. More recently, Yaghoubi, Esfehani, Hosseini, Alikhajeh, & Schultz (2015) also evaluated muscle peak activation order during an overhead shot in water polo players, finding that the optimal proximal to distal sequencing was present in experienced players, but not inexperienced. Serrien, Goossens, & Baeyens (2018) also observed the presence of proximal to distal peak sequencing in their study of elite youth athletes in volleyball. With newer research proving the existence of sequential peak activation in skilled performers, examining coordination patterns may be useful in identifying suboptimal or dysfunctional movement.

Time broadness is another method prominent in the overhead athlete literature used to describe coordination in a movement pattern. It quantifies the time for peak muscle activation relative to the duration of the entire movement cycle, and is calculated by the time elapsed between peaks in EMG activity of the first and last muscles contributing to a particular movement,

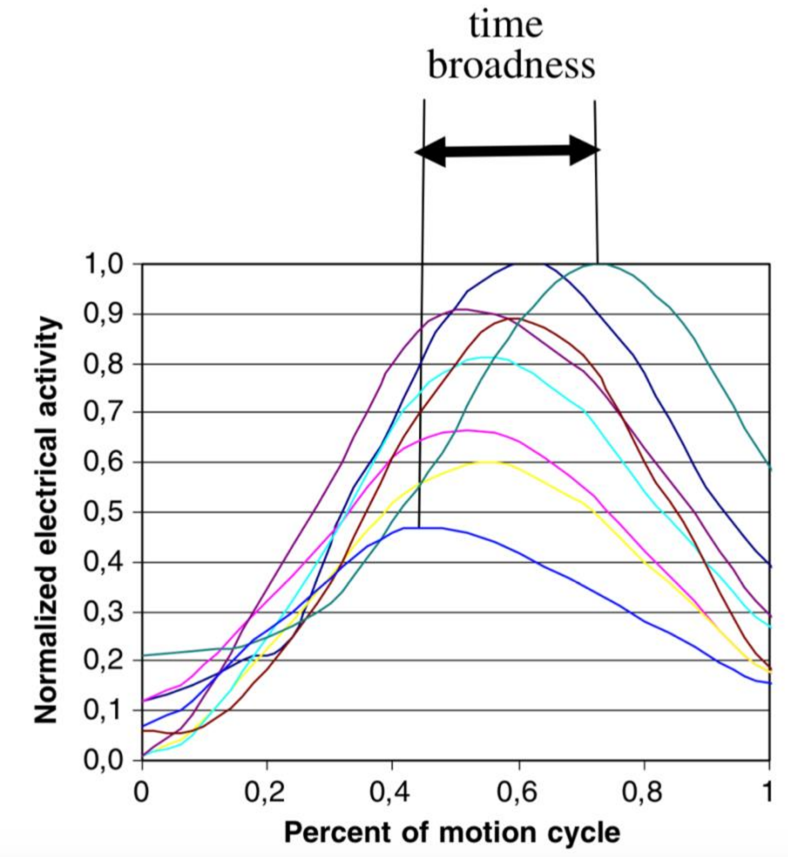


Figure 3. Illustration of time broadness, taken from Illyés & Kiss, 2007

expressed as a percentage of the total time taken to execute a movement.

Time broadness has been evaluated in the research in overhead athletic groups. Yaghoubi et al. (2015) also undertook a comparison of time broadness in their study of water polo athletes. The findings revealed an increased time broadness in the inexperienced group, which indicates a longer time to execute the action. At present, there are no studies that have investigated change in time broadness between groups, nor in response to intervention in volleyball athletes. Zandi, Rajabi, Mohseni-Bandpei & Minoonejad (2018) did however report the reliability of the measure in this population. Results showed good reliability which favours the use of time broadness in future studies with volleyball players.

Time broadness has also been linked to injury in overhead athletes. Illyés & Kiss (2007) compared time broadness in healthy individuals against individuals with diagnosed shoulder instability, finding an increase in time broadness in the unstable group. This finding supports the suitability of time broadness as a measure in studies with links to overhead injury.

In summary, looking at the onset time and time to peak of individual muscles might be of limited use in fatigue and injury research, with further work required to identify the relationship between changes in these measures and development of SIS. However, coordination measures such as onset order, peak order and time broadness seem to be more promising tools for future work. In addition to these variables, there are other outcomes that can give further insight around changes in muscle behaviour. The following sections discuss these variables.

2.4.2 Muscle frequency

Frequency is another variable that can be measured using EMG, and might be useful in assessing shoulder pathologies in fatigued overhead athletes. Frequency can give an indication as to which motor units are being recruited within the muscle. The contractile force produced by a motor unit is proportional to the frequency at which it is activated – that is, higher frequency motor units produce greater force of contraction. Hence a reduction in firing frequency reflects a reduced ability to produce force. Since it is known that decreased force production is an effect of fatigue, it would logically follow that frequency decreases would be observed in fatigued states also. Research on the effect of fatigue on muscle firing frequency appears contradictory across different studies. Katakura, Duffell, Strutton, & McGregor (2011) looked at the quadriceps muscle and recorded decreases in median frequencies during a 60 second maximum voluntary isometric fatiguing task. Gabriel, Basford & An (2001) replicated Katakura et al's findings, studying muscle behaviour during isometric elbow extension in normal and fatigued states. In contrast, Jensen, Pilegaard & Sjøgaard (2000) demonstrated that firing frequency of the deltoid and trapezius muscle groups increased over time, both during and following a prolonged (thirty minute) isometric shoulder abduction trial.

Conflicting results from current research supports the concept of task dependent fatigue responses, with the effects dependant on how the fatigue is elicited. Maximal isometric contractions appear to result in a decrease in firing frequencies (Gabriel et al., 2001; Katakura et al., 2011). Whereas submaximal isometric contractions yielded a decrease in frequency (Jensen et al, 2000). Other research has examined dynamic contractions, with Klich et al (2021) finding reductions in median frequency of the upper trapezius following repetitive internal and external rotation contractions. In addition, one recent study was found that examined muscle frequencies during fatigue caused by volleyball actions. Khal, Moore, Pryor & Singh (2020) found a clinically meaningful (meaning the difference was greater than what may arise through systematic variance) decrease in median frequency of the lower trapezius during a series of serves. Unfortunately, the study did not measure other scapulothoracic muscles. With similar decreases observed in the lower trapezius by Khal et al (2020), and in the upper trapezius by Klich et al (2021), the importance of adhering to the principle of task dependency in fatigue research is once again clear. Furthermore, these results would align with the theory of fatigue altering scapular kinematics and leading to development of SIS. Therefore, there is strong evidence for the use of median frequency in similar studies examining dynamic movements involving the shoulder region.

2.4.3 Muscle amplitude

Muscle amplitude can be a useful indicator of pathologies and potential dysfunction. Researchers can easily measure amplitude through surface EMG, making it a practical tool. Literature has documented amplitude changes in injured shoulders compared to non-injured shoulders (Struyf et al., 2014). This review concluded that, in overhead athlete populations, subjects with SIS had increased activation in the upper trapezius, and decreased activation in the lower trapezius and serratus anterior, compared to healthy controls. These findings contribute towards an understanding of how muscle function is altered, however some caveats exist that must be considered when making interpretations around EMG outcomes.

There are various methods available to researchers for quantifying EMG amplitude, with each being more or less appropriate in different contexts based on their merits. A paper by Renshaw, Bice, Cassidy Eldrgidge, & Powell (2010) compared three common measures calculated from the EMG signal. The authors identified that integrated EMG (iEMG) – that is, area under the EMG curve; and mean root mean square (mRMS) values were near identical, while peak RMS yielded lower values than both former methods. A distinguishing characteristics between iEMG and mRMS is that the former is more sensitive to changes in onset and offset of muscle activity, due to its temporal nature, whereas the latter is less sensitive to changes in amplitude between experimental conditions. All methods involved normalisation to a reference value, most commonly a maximal voluntary isometric contraction (MVIC) so that comparisons can be made easily across groups or conditions. Thus, the most appropriate method of measuring EMG amplitude will differ according to the study design.

Research informs that amplitude can be used to determine fatigue. As fatigue develops, various neurological and physiological mechanisms are altered, which impacts the development, conduction and propagation of action potentials from nervous system to the motor units. With many involved mechanisms, there exist a plethora of potential sources responsible for change in EMG amplitude. Gerdle, Larsson, & Karlsson (2000) reiterated that the effect of fatigue on amplitude depends on multiple factors, including the type and level of contraction, and the specific muscle being activated. With that in mind, there are some observations that are typical of EMG amplitude in certain situations. In isometric maximal contractions that are sustained over time, fatigue develops in the muscle and EMG amplitude will decrease due to a range of factors, including increased inhibitory input from muscle afferents (Taylor et al., 2016). Contrastingly, in submaximal contractions, EMG amplitude in the active muscles *increases* due to greater neural drive, which is a compensatory mechanism to maintain force output (Kaminski & Royer, 2005). Generally these fatiguing methods in studies are limited to one muscle, and achieved using a manual resistance test, isometric hold, or other repetitive lifting through a controlled, small range of motion. However, once again it is important to recognise that these effects are varied according to contexts of muscle function. This is reinforced by Kaminski and Royer (2005), highlighting that upon examination of two EMG signals, without any detail of the activity, there are a number of explanations that could account for different characteristics, such as increased amplitude in one signal compared to the other.

The effects of fatigue caused by other methods are less well researched. Presently, no studies were able to be found that examined EMG amplitude after a sport-specific fatigue protocol, let alone a volleyball-specific protocol. Research has, however, examined strength outcomes in groups of overhead athletes. Two of these studies used sport-specific fatigue in baseball athletes (using pitching), with both reporting decreases in strength (Mullaney, McHugh, Donofrio, & Nicholas, 2005; Reinold et al., 2008). These works are difficult to compare, due to the lack of detail provided around the study design. Despite this, perhaps these studies serve as good examples for researchers to focus on the underlying outcome of force production, rather than EMG amplitude and other variables that are used merely to give an indication of this. Especially given that extraneous factors can easily render EMG measures inappropriate in less controlled settings, care must be taken when interpreting EMG results, and making assumptions about what that means in a functional context for muscle force.

2.4.4 Reliability of muscle activity measures

Reliability is essential in quantitative research to ensure that any observed changes in the outcome measure are a result of the intervention and not a result of systematic error. Previous work has documented reliability measures for shoulder muscle EMG variables. The context of this research is wide and varies among populations (e.g. athletes) and sub-groups of these populations (e.g. injured vs non-injured), as well as in the methods and types of analysis used. Two studies have examined inter-session reliability of RMS EMG activity during unloaded concentric scaption movement (as per the design in the proposed study) (Ludewig & Cook, 2000; Seitz & Uhl, 2012). The first reported on the upper and lower trapezius, as well as the serratus anterior over three joint angle ranges (Ludewig & Cook, 2000), with the second investigating the anterior deltoid, upper and lower trapezius, and serratus anterior (Seitz & Uhl, 2012). The former study reported ICC values between .810 and .850 for the upper trapezius, between .820 and .900 for the lower trapezius, and .730 and .830 for the serratus anterior. The latter reported values of .850 for the anterior deltoid, .700 for the upper trapezius, .620 for the lower trapezius, and .900 for the serratus anterior. According to the framework set by (Landis & Koch, 1977), these values would be rated as substantial at least (ICC ranging from .610-.800), with some being almost perfectly agreeable (ICC > .800). The prevalence of surface EMG measures in test-retest study designs, combined with the reliability of the measures during the scaption movement in particular would indicate that confidence placed in these methods by researchers is justified.

2.4.5 Concluding remarks on muscle activity

In conclusion, findings from the current literature suggest a potential link between fatigue in overhead athletes and SIS, with similar changes in temporal measures observed in both fatigued athletes, and those with SIS. The same suggested link cannot be applied to other shoulder injuries. This observation is well explained by the link between causes of SIS and mechanics of the spiking action. With repeated arm elevation in spiking, it is feasible to assume that the scapula elevator muscles will fatigue over time. In this case, scapula elevation would decrease, due to impairment of these muscles. With reduced scapula elevation comes narrowing of the subacromial space, a known factor in the development SIS (Edwards, Bell, & Bigliani, 2009). It is for this reason that repetitive spiking could plausibly cause SIS, leading to pain and negatively affecting spiking performance.

There is also a need to study fatigue and temporal outcomes in volleyball players. Firing frequencies decline in volleyball players as a result of fatigue induced by serving. Whether or not these changes are observed in volleyball players with a bout of repetitive spiking is unknown. There is a lack of investigation in to muscle amplitudes, as well as coordinative measures in volleyball players with respect to fatigue. There is evidence to support the reliability of such techniques, and thus their use in future studies.

Summary of review of literature

This review aimed to: give a basic understanding of the performance of the volleyball spike; explore injury associations with volleyball and highlight the prevalence of chronic shoulder conditions in particular SIS; and discuss biomechanical factors that may be of importance in the development of these injuries. The evidence is limited at present, but some clear conclusions can be made. Firstly, we understand that the majority of time spent performing the spike is in an overhead position – requiring stabilisation of the scapulothoracic and glenohumeral joints. It has also been highlighted that shoulder internal rotation is a key performance indicator for attacking success. With respect to injury, the evidence reveals that shoulder injuries occur at a rate of roughly 30% in the sport, and that shoulder overuse injuries in particular can keep athletes away from participation for long periods of time. Subacromial impingement syndrome has been identified as a leading injury, and its mechanisms align with the biomechanical demands of the spike. To explore how athletes might protect against, or counteract the mechanism of injury, the outcomes of muscle activity were explored. In particular, temporal measures, firing frequency and muscle amplitude are hypothesised to all play a role in chronic shoulder pathologies, since populations with these injuries often display different patterns compared to "normal" healthy controls. However, the exact response to injury is not clear. The same can be said for fatigued individuals compared to non-fatigued. The measures disussed in this review have been found to be reliable and will be the focus of the proposed study, which will answer the question of how muscle temporal outcomes, activation and coordination measures are affected by overhead fatigue in volleyball. This will add knowledge to the mechanisms of shoulder overuse injuries in volleyball players specifically, which practitioners will be able to use to guide their training, rehabilitative treatment and return to play recommendations.

3 Methods

3.1 Participants

To determine the sample size required for this study, an effect size for fatigue induced changes in median power frequency of the lower trapezius was taken (Khal et al., 2020). Based on a sample size calculation (GPower 3.1) aimed to achieve an effect size of 0.83, with a power of 0.8 and alpha set to 0.05, 11 participants were required for this study. Thus a minimum of 11 participants were sought for inclusion in the study, chosen from a sample of convenience available to the researchers through existing connections with the sport in the region.

3.1.1 Inclusion criteria

To be included in the study, it was determined that individuals should: 1) be able to raise the arm to the overhead position of 127 degrees of shoulder flexion, without pain, 2) at the time of the study, be participating in volleyball at once per week, 3) have previously played volleyball at a structured level such as at organised high school, Club or Provincial competitions, 4) be able to complete the fatiguing task of approximately 5-10 minutes of maximal effort spiking, and 5) be at minimum eighteen years of age.

Current literature does not conclude a specific period of time to return to play following overuse injuries, such as subacromial impingement syndrome (Wilk, Meister, & Andrews, 2002). The general advice is to return as normal function is regained, without pain or discomfort. Therefore, the inclusion of athletes with a history of shoulder overuse problems was evaluated on a case-by-case basis, in accordance with the clinical tests administered during the data collection. Shoulder discomfort while playing volleyball was rated on a numerical pain rating scale (NPRS) from 1-10. Jobe (empty can) and Hawkins tests for signs of impingement were conducted by the primary investigator. All athletes were assessed for overuse symptoms, regardless of pain history.

3.1.2 Exclusion criteria

Participants were to be excluded from the study if they: 1) at the time of the study, were unable to play volleyball for any period of time for any reason, 2) were diagnosed with a traumatic shoulder injury in the past 12 months (e.g. fracture, dislocation, etc), 3) both a) reported pain symptoms greater than 7 on the NPRS scale while playing volleyball and b) displayed positive impingement signs in both the Jobe and Hawkins tests. The NPRS index of 7 was chosen from a study in which outcomes for sixty individuals with SIS were rated and 7 was the mean score for pain during movement in this sample (Lombardi Jr, Magri, Fleury, Da Silva, & Natour, 2008).

3.2 Equipment

Surface EMG was used to assess the activity of the upper, middle and lower trapezius (UT, MT, LT), as well as the anterior head of the deltoid (AD), and serratus anterior (SA) muscles of the hitting shoulder (the arm that the participant would use most often to spike with). Landmarking for electrode placement was performed according to SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles) guidelines. The placement for the anterior deltoid, and UT, MT, and LT electrodes followed the SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles) project recommendations (Hermens et al., 1999). Electrodes for the SA were applied longitudinally (on the most superficial aspect of the muscle): anterior to the Latissimus Dorsi and posterior to the Pectoralis Major, as per prior research (Castelein, Cagnie, Parlevliet, & Cools, 2016). Each electrode location was prepared by shaving, exfoliating with lightly abrasive paper, and cleaning with alcohol. Dual Ag/AgCl surface electrodes, adhesive area of 50 × 25 mm (Noraxon USA Inc) and an interelectrode distance of 20 mm, were attached to the subject at each of these sites. The outline of each of the electrodes were traced to allow the researchers to check for any electrode slippage or movement during between test trials. An inertial measurement unit (IMU), placed at the wrist of the hitting arm, midway between the styloid processes of the radius and ulna, was used to determine the beginning of the arm elevation. A wireless 16-channel EMG system (Noraxon Ultimum, Noraxon USA inc.) recorded the muscle activity, measuring at 2000 Hz.

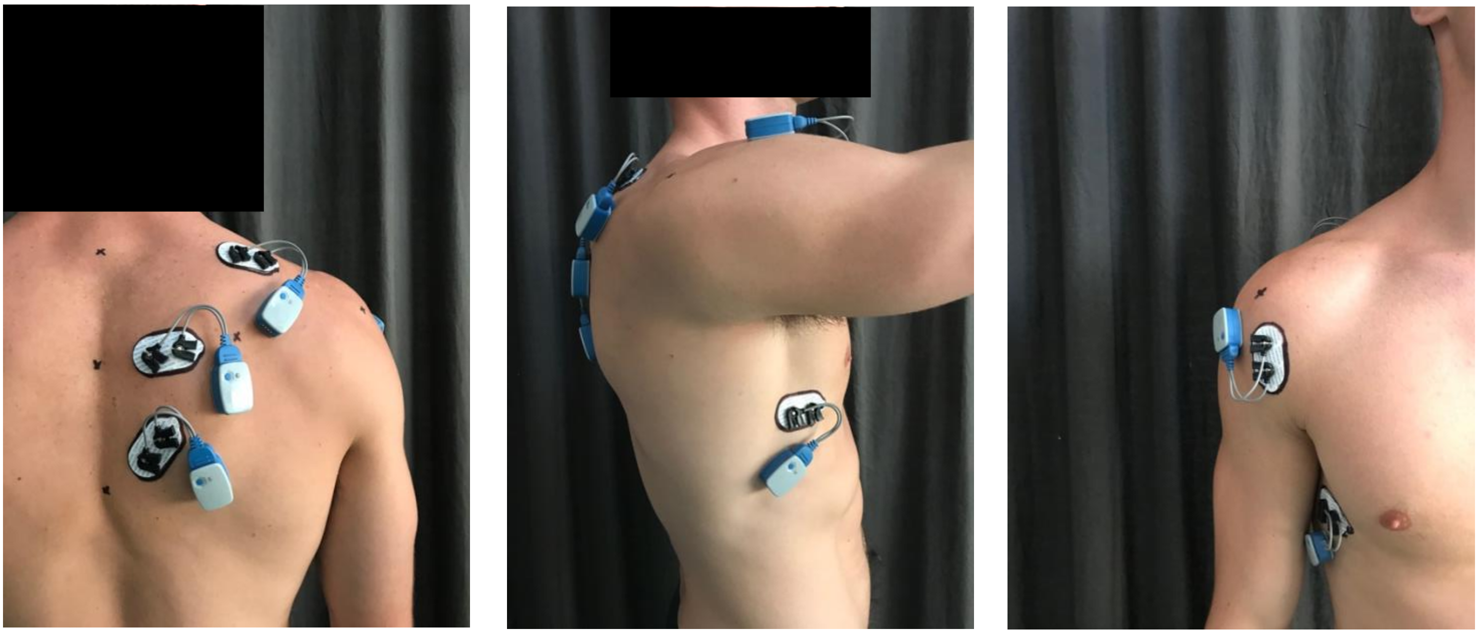


Figure 4. Electrode placement with Noraxon EMG sensors

3.3 Procedure

This study required two sessions for data collection, these were performed in a randomised order for each participant (assignmed using a random number generator). The sessions were performed 24 hours apart. Participants were instructed not to engage in any strenuous physical activity of the upper body 24 hours prior to the first session, nor in between sessions. Both sessions used a rapid arm raise task (or "the measurement task"), described below. The procedure for each testing session follows.

3.3.1 Rapid arm raise assessment task

The task used was adapted from Castelein, Cagnie, Parlevliet & Cools (2016). The participant started standing with the arms in a neutral position (palms facing towards the midline). Participants were instructed to raise the arm as fast as possible, upon hearing an external auditory cue, until they touch a target - marked by a piece of string (chosen so that participants were free to accelerate the limb with maximal intent, and without reservation of colliding with a solid object at the end). This target was set to 127 degrees, a value based on prior research (Plawinski, 2008), which investigated arm swing mechanics in elite men's volleyball, and found that mean maximum shoulder abduction angles varied from 119 to 127 degrees during attack hits. On performance of the task, the investigator gave the participant a “ready” warning, prior to the movement cue, then triggered the cue with a trigger synchronised to the data collection software. Familiarisation trials took place before data collection, and then a brief rest period was be allowed before testing began. The testing used ten repetitions of the arm raising task, performed consecutively with a few seconds rest between trials.

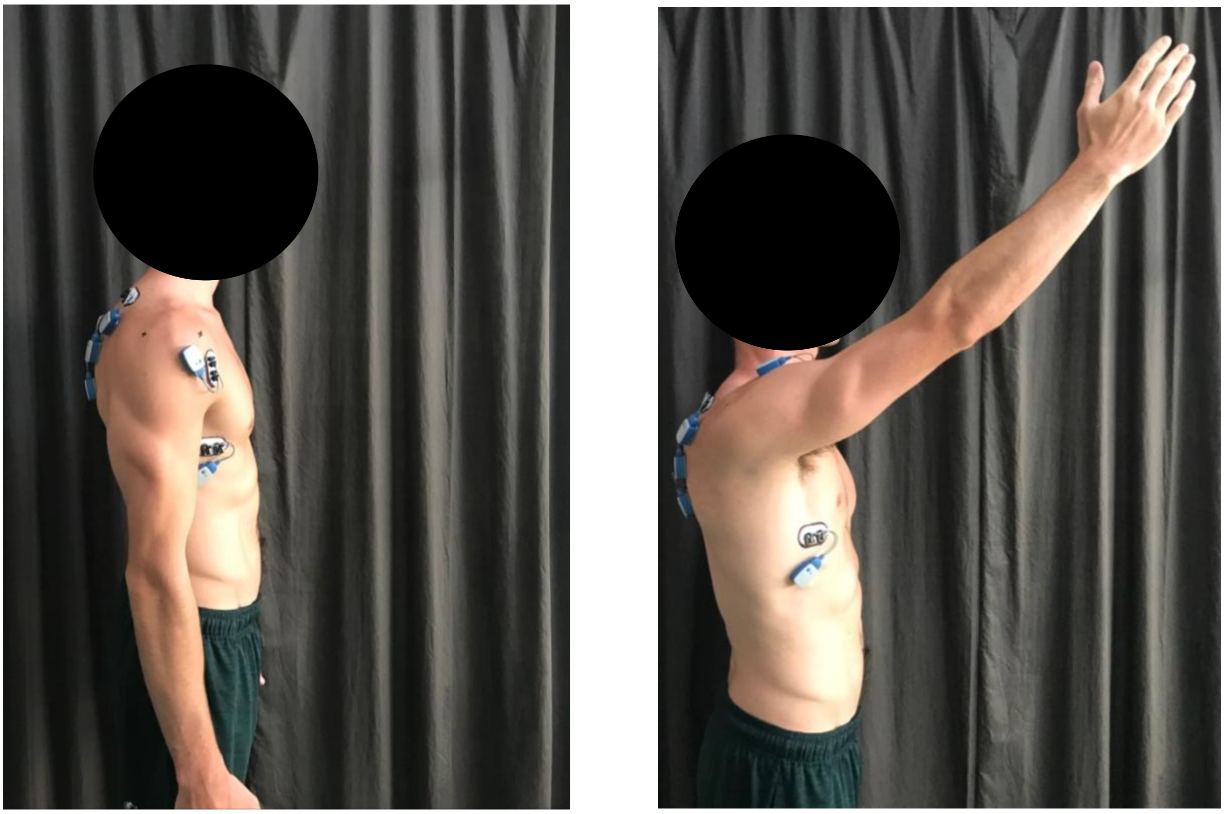


Figure 5. Start and finish position for the rapid arm raise task

3.3.2 Reliability testing session

To assess the trial-to-trial reliability of the muscle activity measurements without the effect of the intervention, participants were assessed at two different time points during the same session. This session began with applying the electrodes as per the process described in section 3.2. Then, participants underwent a volleyball hitting-specific warm up, the design of which was based on prior research (Khal et al., 2020). The warm up consisted of the following exercises designed to activate the scapulothoracic musculature at low levels: wall slides, back to wall shoulder flexion in the scapula plane, theraband resisted internal and external shoulder rotation in an abducted position, and a series of two minutes of "warmup hits" at 50% effort against a wall. Following this warm up, the Noraxon sensors were connected to the electrodes and secured with adhesive strips, the IMU was also attached at the wrist in this manner. Sensors were further secured using velcro straps. Data were collected while performing the measurement task. The participant then sat for 30 minutes before repeating the measurement task a second time, in the exact same manner as the first. In addition to testing the reliability, these trials also served to identified any potential confounding variables. For example, if a subject with a history of injury had greater variability between trials, this would need to be accounted for in the data analysis. Following the second measurement task, maximal voluntary isometric contraction (MVIC) testing was performed to gain reference values for each muscle's EMG activity. The MVIC protocol is detailed below.

3.3.2.1 MVIC testing procedure

All testing was performed by the primary investigator. Maximal voluntary isometric contraction testing for each muscle was conducted against manual resistance, for a duration of 5 seconds. Each test was repeated 3 times, with a 30 second rest period between repetitions. Anterior deltoid was tested with the shoulder flexed to 90 degrees, against downward manual resistance applied above the elbow. The upper trapezius assessment used the "seated T" test, with the shoulder abducted to 90 (elbow fully extended) and resistance applied above the elbow, in a downward direction. The assessment of the middle trapezius used the "prone T thumbs up" test, with the shoulder horizontally abducted and externally rotated (elbow fully extended) resisting manual pressure downward, from above the elbow, to resist adduction of the scapula and extension of the shoulder. The "prone V thumbs up" test was used for the lower trapezius, which sees the arm raised above head in line with lower trapezius muscle fibers (elbow fully extended) as resistance applied above the elbow against further arm raise. Serratus anterior was assessed by the “seated U 135 degrees” test, with the shoulder flexed to 135 (elbow fully extended) as resistance is applied above the elbow against further arm raise (Castelein, Cagnie, Parlevliet, Danneels, & Cools, 2015; Konrad, 2005).

3.3.3 Repetitive spiking intervention session

On the second day the participant completed the warm-up and initial measurement task as per section 3.3.1. This was followed by the fatiguing protocol then a repeat the of the measurement task. EMG sensors were disconnected prior to the fatiguing task, both due to comfort of the participant, and the risk of damaging the sensors by falling off in high velocity movement. During the fatiguing task each participant performed multiple sets of seven standing spikes in to a catching net (see Figure 6). For each set of spikes, the participant was passed balls by the investigator, to ensure quick succession. The following instructions were given to participants: “Spike the ball as hard as possible, and as fast between repetitions as possible. You’ll start a new set every 30 seconds, so the faster you complete the spikes, the more rest you will get.” This instruction was to maximise the participant’s exertion. RPE was collected at the end of each set, using a 15-point Borg scale. The fatiguing protocol concluded when participants reach an RPE of 15, after a minimum of six sets. This is greater than the RPE threshold at which Khal et al (2020) validated that fatigue was indeed present by measuring median power frequency. The post-intervention measurement arm-raising task was performed as soon as practically possible, after reconnecting the EMG sensors. Prior to the task, the electrodes were checked to ensure adhesion had been maintained, there was appropriate skin contact, that the electrodes had not moved from the original position and signal quality was good. The post-fatiguing measurement task followed the same protocol as the first instance.

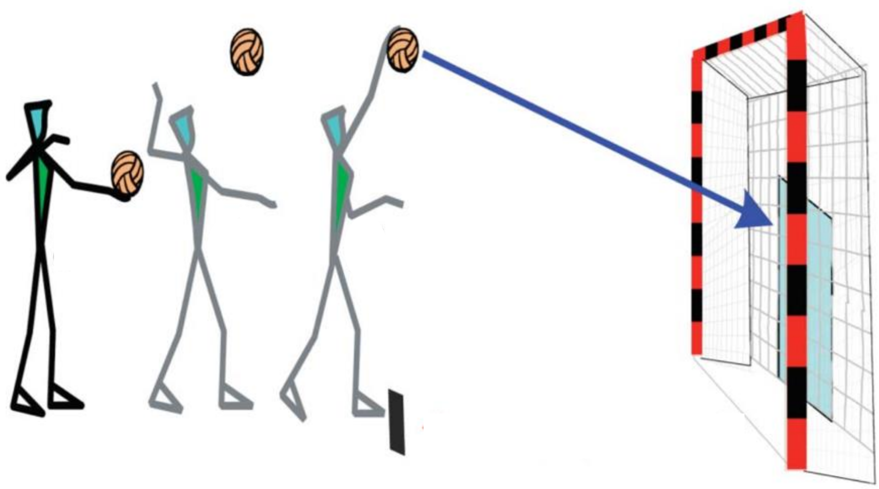


Figure 6. Illustration of the set up for the repetitive spiking task

3.4 Data analysis

All data processing was performed in MATLAB (Version R2021, Mathworks) using custom written code. From each testing session, five good trials were used for analysis. Good trials were defined as those that could accurately determine the beginning and end of the movement cycle (described in the next section). If there were more than five good trials, five were selected at random using a random number generator. Data were averaged across the trials (Castelein et al., 2016). The variables obtained from the trials are detailed in the following subsections.

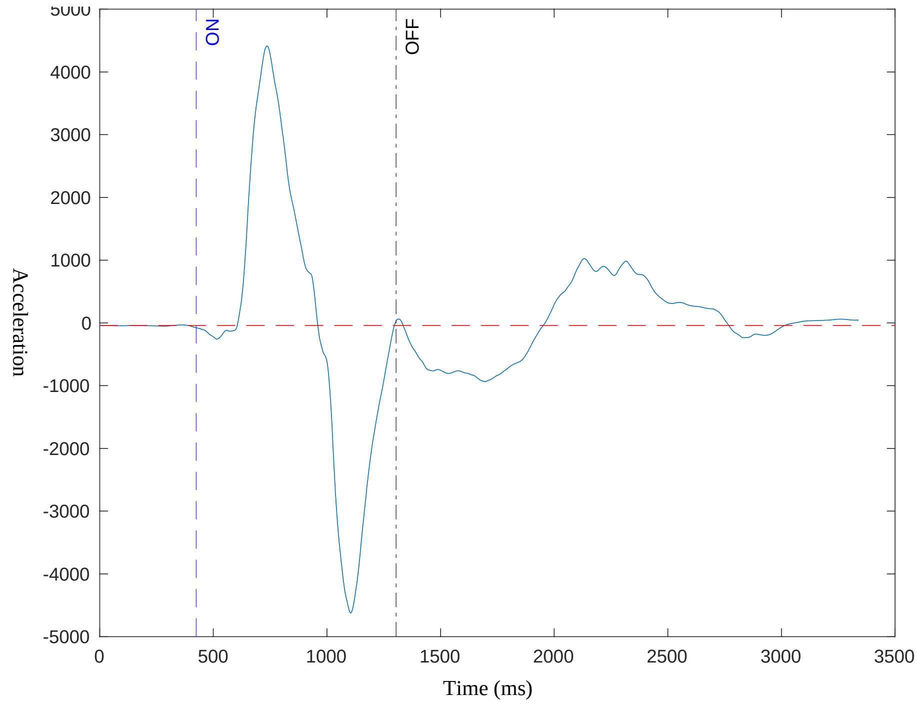


Figure 7. "Good" acceleration profile from wrist IMU used to determine onset and offset of movement

3.4.1 Kinematic data

Kinematic data were extracted from the wrist IMU accelerometer worn during the arm raising task. The data were used to identify the beginning and end of the movement cycle, by visually identifying the beginning of the movement by the point where the accelerometer data began increasing from the baseline level, as determined algorithmically using an increase of 3 standard deviations from the initial 100 ms of data as established in prior research (Hodges & Bui, 1996). The end of the movement was determined to be where the acceleration returned to zero after having accelerated in a positive and negative direction - indicating the arm movement had ceased. The identified values were visually verified using a MATLAB GUI. A ‘good’ sample trial is displayed in Figure 7, whereas a rejected trial is pictured in Figure 8.

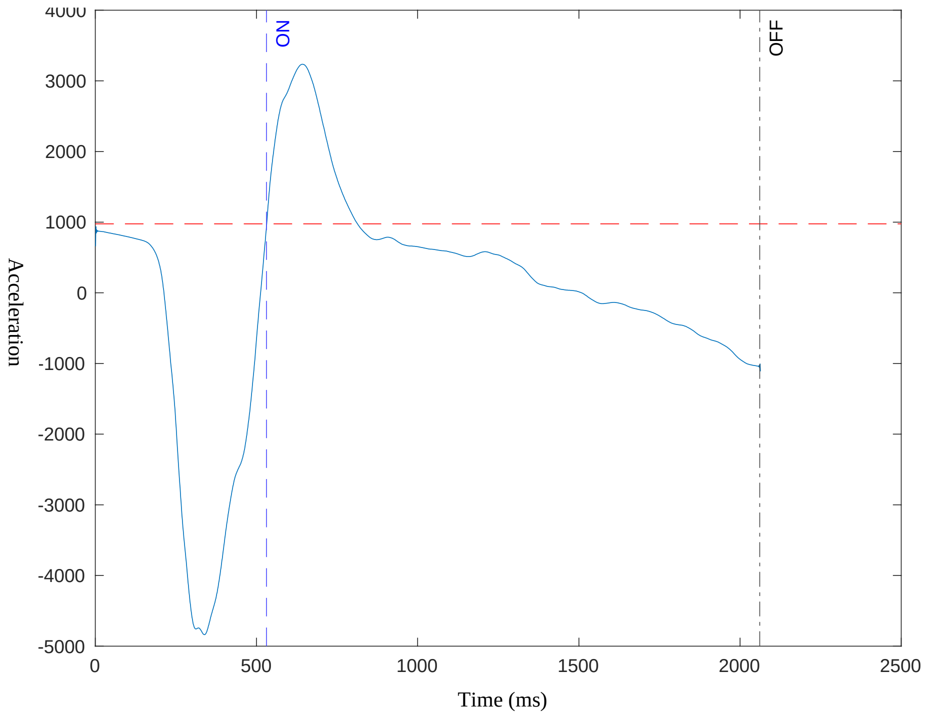


Figure 8. Rejected acceleration profile with erroneous baseline and incorrectly determined beginning and end points of movement.

3.4.2 Area under EMG curve

The raw EMG data for each trial was processed using a bandpass filter from 20 to 500 Hz. The RMS of the filtered data were taken using a 50 ms window and was used in the analysis of muscle activity. To give an indication of muscle amplitude, area under the EMG curve was calculated using the trapezoid method for the time period encapsulated by the duration of the movement cycle (as defined above). This measure was then normalised to the respective muscle's area under the MVC curve, for an equal period of time centred around the MVC peak. Amplitude values are reported as percentages of MVC.

3.4.3 EMG peak amplitude

The peak EMG amplitude, defined as the maximum absolute value of the filtered RMS signal, during the ascending phase of the movement cycle was obtained, and expressed as a percentage of the peak MVC amplitude value.

3.4.4 EMG frequency

EMG frequency of each muscle was obtained from the filtered raw data by calculating the median frequency of the signal for the duration of the movement cycle. Frequency data are presented in hertz (Hz).

3.4.5 Temporal variables

Time to peak for each muscle was calculated for each trial. The peak time of the prime mover (anterior deltoid) was used as a reference point, with positive time values indicating peaks occurred after that of the deltoid, and negative values indicating the peak preceded the deltoid's. Time to peak values were also used to calculate time broadness, calculated as the elapsed time between the peak of the first muscle and the peak of the last muscle. Time broadness is expressed relative to the duration of the movement cycle, and is presented as a percentage value. See subsection 2.4.1 of this thesis for a further description of this measure.

3.5 Statistical analysis

Statistical analysis was carried out using SPSS 27.0 (IBM Corp., Chicago, IL). Intra-class correlation coefficients (ICCs) (two-way random, absolute agreement) were performed to assess the reliability of the measured variables. Both intra- and inter-day reliability was considered, intra-day by comparing the first and second measures in the control session, and inter-day by comparing the first measure of the reliability session with the first measure of the intervention session.

EMG characteristics (amplitude and frequency) and temporal variables (time to peaks and time broadness) were anlaysed using a generalised linear mixed model to examine differences between pre and post-intervention measures.

A Friedman rank test, with significance set at $p < .05$, was employed to determine if any changes in the order of sequential muscle activation were present between conditions. Ranks were examined in the first control measure, the pre-intervention measure and the post-intervention measure, allowing inferences to be made about the effect of the intervention on the coordination of muscle activity. Wilcoxon signed rank tests were performed post hoc to determine which conditions differed in muscle rankings, with significance set at $p < .017$, using a Bonferroni correction for three comparisons being made.

4 Results

4.1 Demographic information

Table 1. *Demographic information of included participants*

	Mean (SD)
Age	22.0 (3.6)
Height	186.5 (5.6)
Mass	85.0 (11.1)
Playing age	7.4 (3.0)
Average pain score while playing currently	1.6 (2.0)

Of the 13 included subjects in this project, 12 were right-handed and one was left handed. Participants demographic information are displayed in table 1. None reported any current shoulder conditions, however three reported having missed playing time due to injury. The scores for evaluating pain while currently playing volleyball had an average of 1.6 (2.0) out of 10 on the NPRS. Only one participant returned a postive result in the Hawkin's and

Jobe clinical screening tests, and this participant was included based on not meeting the other exclusion criteria.

4.2 Reliability testing of measures

The ICC values were interpreted according to the guidelines set out by (Landis & Koch, 1977). Peak amplitude values of all muscles were deemed to be almost perfectly agreeable on an intra-day basis, with ICC values ranging from .895 to .979. Comparing inter-day measures indicated almost perfect agreement for the UT, MT and SA, with substantial agreement for the AD and the LT.

Almost perfect agreement was observed for the intra-day reliability of the amplitude for all muscles (.895 to .979), indicating that this is a reliable measure and that similar amplitude values can be expected at different time points on the same day, assuming similar testing conditions. The inter-day reliability was almost perfect for the AD, UT and SA, with 'substantial' agreement for the MT and LT.

All muscle's frequency measures had almost perfect agreement for intra-day reliability, with the ICC values ranging between .871 and .966. Again, from these results it can be expected that with similar testing conditions, frequency measurements at different time points on the same day

Table 2. *Intra- and inter- day means and ICC values (95% C.I.) for all variables*

Variable		Control pre mean	Control post mean	Same day ICC (95% CI)	Next day pre mean	Day to day ICC (95% CI)
Peak amplitude (% MVC)	AD	88.98 (23.01)	81.76 (21.51)	0.902 (0.626, 0.972)	82.73 (19.42)	0.731 (0.117, 0.921)
	UT	60.62 (29.00)	59.36 (29.90)	0.981 (0.935, 0.994)	53.81 (26.82)	0.957 (0.793, 0.989)
	MT	40.62 (16.80)	40.62 (16.80)	0.924 (0.728, 0.978)	38.64 (14.60)	0.873 (0.563, 0.963)
	LT	60.21 (26.31)	61.77 (24.08)	0.976 (0.919, 0.993)	60.79 (19.21)	0.686 (-0.174, 0.911)
	SA	63.85 (22.08)	59.74 (20.59)	0.896 (0.634, 0.972)	62.44 (18.54)	0.900 (0.624, 0.973)
Area under EMG curve (% MVC)	AD	3.07 (1.34)	2.96 (1.15)	0.976 (0.923, 0.992)	2.96 (1.01)	0.831 (0.438, 0.949)
	UT	2.17 (1.45)	2.12 (1.36)	0.979 (0.933, 0.994)	2.06 (1.13)	0.957 (0.862, 0.987)
	MT	0.99 (0.24)	1.01 (0.31)	0.895 (0.658, 0.968)	1.04 (0.33)	0.637 (-0.220, 0.890)
	LT	1.74 (0.95)	1.73 (0.87)	0.979 (0.931, 0.994)	1.65 (0.57)	0.741 (0.129, 0.922)
	SA	2.41 (0.84)	2.32 (0.80)	0.952 (0.848, 0.985)	2.53 (1.08)	0.860 (0.545, 0.957)
Frequency (Hz)	AD	77.3 (17.1)	74.9 (13.9)	0.903 (0.692, 0.970)	75.3 (10.6)	0.785 (0.291, 0.934)
	UT	88.4 (17.7)	89.6 (20.1)	0.882 (0.608, 0.964)	85.4 (18.4)	0.802 (0.359, 0.940)
	MT	79.9 (27.5)	85.3 (37.5)	0.955 (0.853, 0.986)	81.8 (29.0)	0.960 (0.870, 0.988)
	LT	63.0 (11.0)	63.1 (11.6)	0.871 (0.565, 0.961)	61.5 (12.7)	0.566 (-0.511, 0.870)
	SA	61.1 (19.9)	61.9 (24.9)	0.966 (0.889, 0.990)	57.7 (13.3)	0.466 (-0.842, 0.839)
Time to peak (ms)	UT	-16.28 (152.4)	-18.6 (120.9)	0.955 (0.853, 0.986)	13.75 (165.2)	0.955 (0.848, 0.987)
	MT	-25.14 (137.8)	-63.19 (122.5)	0.822 (0.448, 0.945)	75.65 (105.7)	0.682 (-0.148, 0.909)
	LT	-23.23 (181.9)	-68.8 (150.7)	0.952 (0.746, 0.987)	71.91 (163.6)	0.716 (0.115, 0.912)
	SA	95.47 (149.9)	112.31 (179.2)	0.889 (0.637, 0.966)	169.5 (151.7)	0.804 (0.304, 0.942)
Time broadness (%)		45.09 (14.70)	44.44 (13.68)	0.575 (-0.510, 0.873)	49.21 (15.53)	0.672 (-0.041, 0.899)

Abbreviations: Anterior Deltoid (AD), Upper Trapezius (UT), Middle Trapezius (MT), Lower Trapezius (LT), Serratus Anterior (SA) will be similar. The UT and MT had almost perfect intra-day reliability, with the AD being substantial, and the LT and SA being moderate.

The time to peak of all muscles proved to be highly reliable, with intra-day ICC values ranging from .822 to .955, indicating almost perfect agreement. Inter-day reliability was almost perfectly agreeable for the UT and SA, and substantially agreeable for the MT and LT.

Time broadness was also assessed for reliability, indicating moderate agreement for the intra-day measures, and substantial agreement for inter-day measures.

4.3 Effect of repeated spiking on pre-post measures

4.3.1 EMG peak amplitude

The difference in EMG peak amplitude between pre and post measurements was statistically significant for the AD only ($F_{1, 106} = 6.199$, $p < .05$), which had a mean difference of -5.194%. This result indicates that the fatiguing intervention decreased the peak amplitude in the post-intervention measurement, compared to the pre-intervention measurement. All other muscle differences in peak amplitude were non-significant.

Table 3. *Results from the generalised linear mixed model (GLMM) assessing pre- and post-intervention differences in all variables. Negative values indicate a decrease at the post-intervention measurement. Significance level p < 0.05.*

Variable	Muscle	Mean (F-N)	Lower C.I.	Upper C.I.	t	*p*
Peak amplitude (% MVC)	AD	-5.194	-9.329	-1.058	-2.490	**.014**
	UT	-1.415	-5.071	2.242	-0.762	.447
	MT	1.200	-3.002	0.601	-1.313	.191
	LT	1.945	-3.518	7.407	0.701	.484
	SA	0.644	-3.621	4.909	0.297	.766
Area under EMG curve (% MVC)	AD	-0.173	-0.335	-0.01	-2.488	**.040**
	UT	-0.018	-0.133	0.097	-0.313	.755
	MT	0.048	-0.166	0.263	1.343	.346
	LT	0.164	0.069	0.259	3.406	**.001**
	SA	-0.005	-0.121	0.111	-0.088	.930
Frequency (Hz)	AD	0.783	-4.083	5.65	0.355	.730
	UT	2.581	-2.868	8.031	1.156	.291
	MT	0.236	-7.701	8.174	0.076	.942
	LT	7.279	2.657	11.901	3.493	**.006**
	SA	0.211	-8.673	9.096	0.051	.960
Time to peak (ms)	UT	-13.007	-412.333	386.32	-0.854	.581
	MT	-40.821	-67.577	-14.065	-3.033	**.003**
	LT	-36.64	-67.393	-5.887	-2.389	**.020**
	SA	22.517	-9.757	54.792	1.393	.168
Time Broadness (%)		0.601	-2.991	4.192	0.330	.742

Abbreviations: Anterior Deltoid (AD), Upper Trapezius (UT), Middle Trapezius (MT), Lower Trapezius (LT), Serratus Anterior (SA)

4.3.2 Area under EMG curve

For muscle areas under the curve (AUC), four of five muscles exhibited no significant change between pre-and post-intervention measurements. The GLMM yielded high p-values and C.I.s that include zero for the UT, MT, LT and SA, displaying no change in either the positive or negative direction. There was a statistically significant mean difference in the AUC of the AD, decreasing from the pre- to the post-intervention measurement by 0.173%, with a C.I. from -0.335 to -0.01% ($F_{1, 7} = 6.19$, $p < .05$).

4.3.3 Frequency

The analysis revealed no statistically significant changes in muscle median frequency aside from in the LT ($F_{1, 10} = 12.204$, $p < .01$), which had a mean difference of 7.279 Hz [2.657, 11.90] between the post and pre intervention measures. The C.I. of the difference is entirely above zero, meaning it can be said with 95% certainty that the true mean difference lies in this range. With this result, it can be said that the spiking induced an increase in median frequency. The frequency of all other muscles did not change following the spiking bout, nor were there any results that indicated trends in median frequency differences.

4.3.4 Time to peak amplitude

The generalised linear mixed model indicated statistically significant decreases in the time to peak amplitude of the MT ($F_{1, 85} = 9.201$, $p < .01$). The mean difference between the post and pre-intervention measurements was -40.8ms, with a 95% C.I. between -67.6 and -14.1ms. Since this interval is entirely below zero, it can be said with 95% confidence that the true mean difference is negative, indicating lesser time to MT peak amplitude following the spiking bout.

Differences were also observed at a statistically significant level for the time to peak of the LT. A decrease between the pre and post condition was observed ($F_{1, 54} = 5.706$, $p < .05$), with a mean difference between measurements of -36.6ms [-67.4, -5.9]. Again, the confidence interval is entirely below zero so the results indicate that the true mean difference is negative. This can be interpreted with 95% confidence that the time to LT peak amplitude is lesser as a result of the intervention. Neither the UT nor the SA yielded significant results, although the SA appeared to trend towards an increase in time to peak amplitude in the post measurement, with a mean difference of 22.5ms, and the majority of the confidence interval above zero [-9.8, 54.8].

4.3.5 Time broadness

Time broadness did not differ significantly between the pre and post measurements. The mean difference was 0.601%, with a 95% confidence interval that includes zero. This indicates no trend between the two measurements.

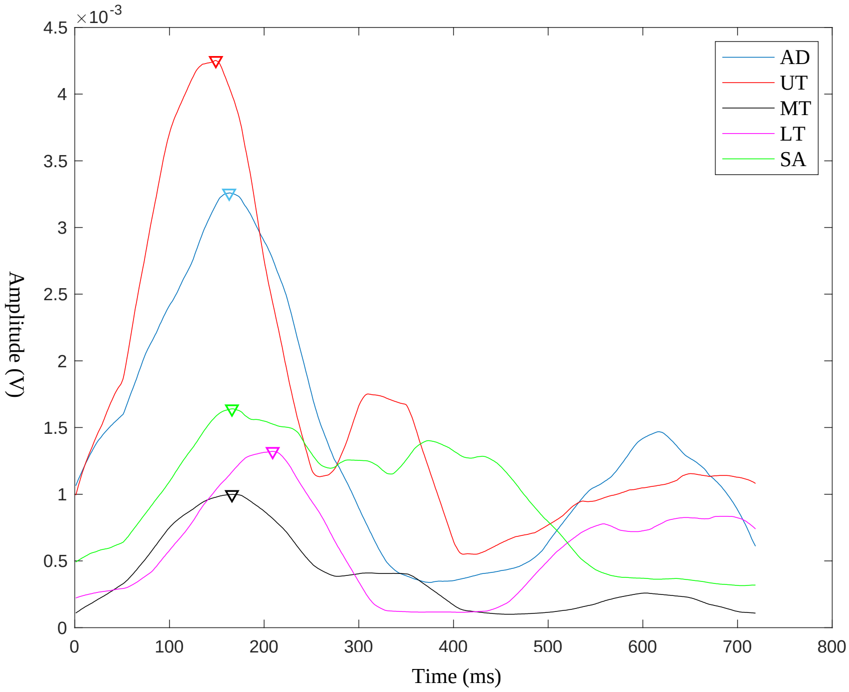


Figure 9. Illustration of time broadness of muscle peaks in a single trial in the pre-intervention condition

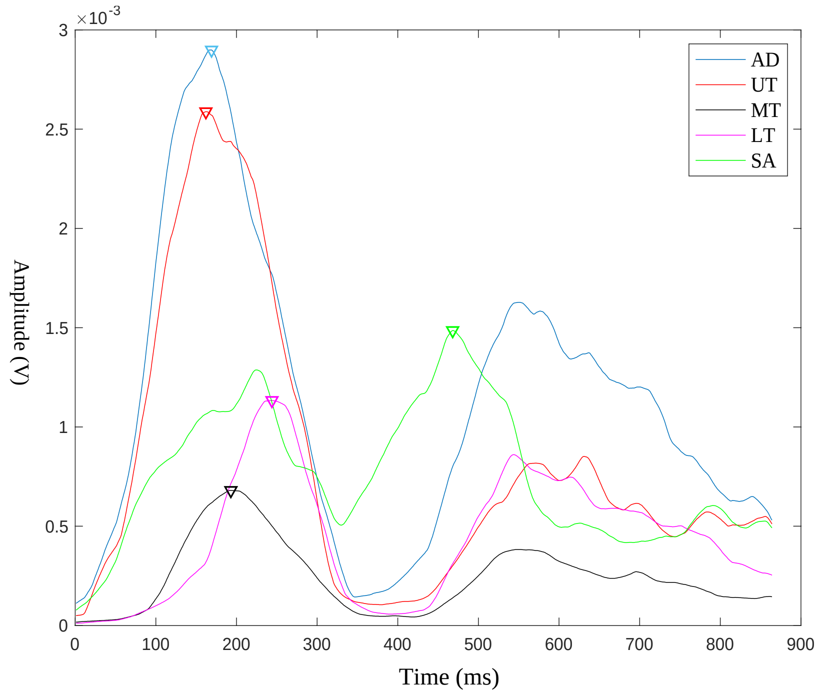


Figure 10. Illustration of time broadness of muscle peaks in a single trial in the post-intervention condition

4.5 Rank order of muscle peaks

Table 4. *Mean ranks of peak amplitude order from the Friedman rank test in control, pre- and post-spiking conditions. Significance level p < 0.05.*

Muscle	Control	Pre	Post	*p*-value
AD	2.12	1.88	2.00	.075
UT	2.05	2.00	1.95	.669
MT	1.84	2.22	1.95	.002*
LT	2.01	2.06	1.93	.497
SA	1.90	1.90	2.20	.002*

A Freidman's rank test was performed to determine differences in rank order of EMG peaks across conditions. The analysis revealed no statistically significant differences in order of peak amplitude for the AD, UT and LT. However, there was a statistically significant difference in both MT and SA peak order, $\chi^2(2) = 12.583$, $p < 0.01$, and $\chi^2(2) = 12.642$, $p < 0.01$ respectively.

Table 5. *Results of the Wilcoxon signed rank tests for muscles that displayed significant differences in rank order. Significance level p < 0.017.*

	Mid-trapezius		Serratus-anterior	
	Z-score	*p*-value	Z-score	*p*-value
Pre-Control	-.216	.829	-3.489	<.001*
Post-Control	-3.130	.002*	-1.065	.287
Post-Pre	-3.087	.002*	-2.946	.003*

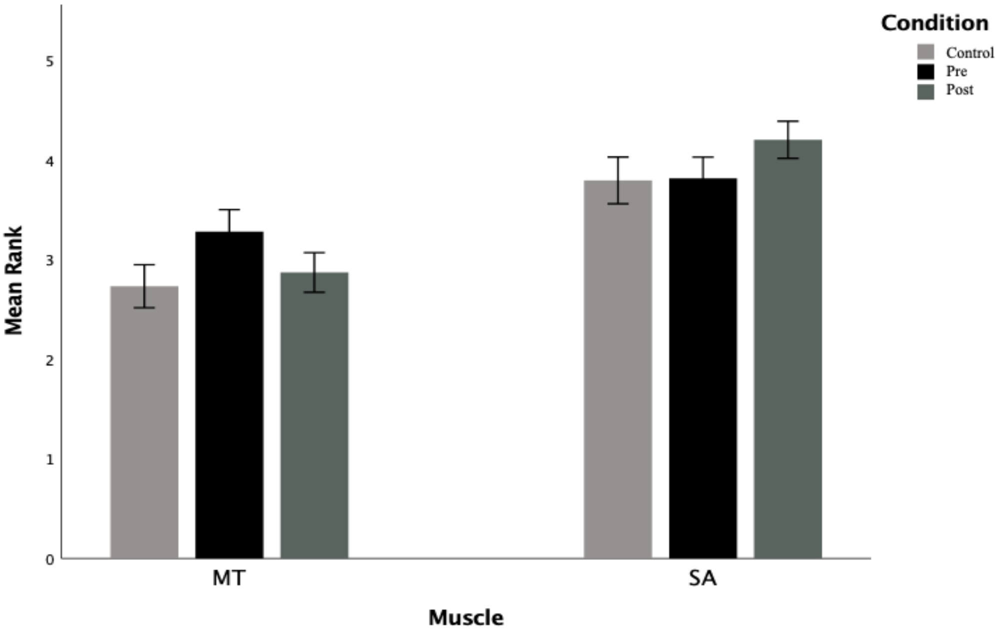


Figure 11. Mean rank order of the peak amplitude of the middle trapezius and serratus anterior across time measurements

Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.017$. For the MT, there were no significant differences between the control and post-intervention measurements (Z =-1065, p =0.287). However, there was a statistically significant increase in the position of MT peak in the pre condition compared to the post condition (Z =-2.946, p< 0.01) and also the control condition (Z =-3.489, p =0.001). For the SA, there were no significant differences between the control and pre measurements (Z =-0.216, p =0.829). However, there was a statistically significant increase in the position of SA peak in the post compared to the pre condition (Z =-3.087, $p < 0.01$) and the control condition (Z =-3.130, $p < 0.01$).

5 Discussion

The purpose of this research was to investigate the effect of fatigue caused by repetitive spiking on shoulder muscle activation during a rapid arm raise task. While it has been suggested that muscle fatigue may be a precursor to overuse injury, in particular subacromial impingement syndrome, in repetitive overhead movements no prior literature has investigated the effect of fatigue caused by spiking in volleyball players. The findings of the current study give insight into how the volleyball player's shoulder functions in a fatigued state. The EMG data from this study confirmed changes in muscle function after a high intensity bout of repeat spiking activity. In this chapter, these changes in muscle function are addressed by discussing each outcome variable. Various theories are explored that explain the observed results, including physiological, neurological and contextual factors. Finally, implications of the findings are discussed, with suggestions for future research in this area.

5.1 Reliability

The ICC values, as reported in Table 2, indicate the variables used in this study were highly reliable in both day-to-day and trial-to-trial measures. However, the confidence intervals of the ICC values are very wide for some variables, which calls in to question the true reliability of these measurements. As such, we cannot say with certainty that such measures are reliable. Despite this, other work has repeatedly indicated high reliabiilty of the measurements used in this research. The time domain variable (Cools et al.) of the EMG has been consistently reported to be highly reliable in dynamic movements, such as the one used in the present study (Ludewig & Cook, 2000; Seitz & Uhl, 2012). Research also indicates that reliability of the RMS measure is maintained in more functional contexts. Whereas Ludewig & Cook (2000), and Seitz & Ugl (2012) both used simple laboratory-based arm raising tasks, (Zandi et al., 2018) examined reliability of EMG measures in a functional spiking task. Zandi et al. (2018) reported high day-to-day and trial-to-trial reliability, indicating that surface EMG is an appropriate tool in assessing activity during a spiking task. Future research around muscle activation in volleyball can confidently use EMG repeated measures during spiking performances.

5.2 Peak amplitude and area under EMG curve

The repetitive spiking procedure elicited significant changes in EMG peak amplitude in the AD and area under the EMG curve in both the AD and LT. It was hypothesised that both peak amplitude and area under the curve would increase, as they are both measures of muscle amplitude. Much literature has documented amplitude increases with submaximal fatigue due to increased neural drive to compensate for losses in force output. Therefore, due to the nature of the fatiguing protocol used in this study, similar increases in EMG amplitude of all muscle were predicted. Contrary to this expectation, changes in peak amplitude during the measurement task were observed in the AD only, exhibiting a decrease in mean difference between pre and post measurements. The peak amplitude of all other muscles was unchanged. The decrease in peak amplitude was accompanied by decreased area under the EMG curve for the AD. Area under curve measures revealed one other interesting result, finding increased area under the curve found for the LT. Both peak amplitude and area under the curve are representative of amplitude, therefore the result in the AD is contrary to, however the LT result aligns with the hypothesis. The fact that there was no change in muscle activity measures for the UT, MT and SA suggest that a level of fatigue sufficient to produce changes was not elicited in these muscles by the repetitive spiking. This may be due to the fact that these muscles are less active during spiking, and as such do not fatigue as quickly as the more active LT and AD. However, this is not supported by research since it has been shown that LT in less active than SA in all phases of the spiking action, and less active than the MT and UT in some phases (Miura et al., 2020). The differing amplitude responses of the LT to the UT, MT, and SA in this context cannot be easily explained, and require further investigation.

With the AD decreasing and LT increasing in amplitude following the spiking protocol, it can be interpreted that the two muscles responded differently. Considering their different functions during the spiking motion, it can be assumed that the AD and LT were fatigued in different ways. The decrease in amplitude seen in the AD indicates that the fatigue was near-maximal, since decreases in amplitude occur as a result of increased inhibitory afferent input from the muscle to the motoneurons, among other mechanisms (Taylor et al., 2016). Near-maximal fatigue is plausible, with the AD having a large contribution to the windup phase of the spike (Rokito et al., 1998), and continuing to be active throughout all subsequent phases.

The LT demonstrating an increase in amplitude indicates it was fatigued in a submaximal manner, in which the nervous system upregulates central drive to compensate for loss in force production (Kaminski & Royer, 2005). The potential development of submaximal fatigue is consistent with the role of the LT during the spike, acting in a stabilising capacity. An alternative explanation for the increase in LT amplitude is that this was not a direct result of fatigue in the LT, but a compensatory mechanism for changes in other muscles. Greater amplitude could indicate a volitional increase in activation in order to produce more force, however, as previously highlighted in this thesis, it is difficult to make inferences about force production based on EMG alone. Moreover, the fact that no changes were observed in the amplitude of other scapula muscles brings doubt around the fact that the LT would be compensating for loss of force elsewhere.

5.3 Frequency

Repetitive spiking resulted in significant increases in the firing frequency of the LT, which does not align with the hypothesis of the study. Research shows that multiple, short contractions elicit frequency decreases in active muscles (Klich et al, 2021). Consequently, decreases in frequency were expected to be found in the present study due to repetitve spiking requiring multiple brief contractions of the working muscles.

In the present study, the LT demonstrated a significant increase in the mean difference between pre and post measurements. Research has produced findings to the contrary. In one study, median frequency of the lower trapezius was measured during repetitive volleyball serving over time (Khal et al., 2020). These authors noted a decrease in LT frequency, although not statistically significant. However, this decrease was *clinically significant*, meaning the difference was greater than what may arise through systematic variance (Oberg, Sandsjo & Kadefors, 1990), and the result exceeded Cohen's convention for a large effect (d = 0.83). Khal et al's study was revealed to be insufficiently powered, which opens the possibility that their observed decreases in LT frequency may be statistically significant with greater power. The contrasting observations in both the present study and that of Khal et al (2020) make it difficult to ascertain the effects of volleyball induced fatigue on the median frequency of the LT. Here, two possible explanations for the observed result in the present study are proposed.

The first is that, during the spiking procedure, lower frequency units became fatigued, but not the high frequency units. Higher frequency units are capable of producing more force than their lower frequency counterparts (Purves, 2001). Since the lower trapezius acts as a stabiliser to maintain the position of the scapular during overhead movement, this role requires low levels of force sustained over a longer period of time, hence there is less need for powerful muscle activation. If the lower frequency units were fatigued during the repetitive spiking, more higher frequency units may have been recruited over time to compensate for this, manifesting in a higher median frequency measurement post fatigue. This hypothesis may also explain other findings of this research – namely why there were no changes in amplitude parameters for the lower trapezius. If higher frequency units within the muscle become active under fatigue to maintain force production, this would explain why no differences in amplitude were observed for this muscle.

The second proposed reason for the observed in frequency changes is that the metric of median frequency is unreliable in dynamic movements, thus is inappropriate for use in the context of this research. Median frequency is typically used to assess static (isometric) contractions, compared to dynamic movements as was the case in the present study. There have been very few studies that have attempted to quantify fatigue using median frequency in dynamic movements. In dynamic movement, alterations in muscle length occur as a result of joint angles changing. This in turns changes the length-tension relationship, and as such the activation characteristics of the muscle fibres (Arendt-Nielsen, Gantchev & Sinkjær, 1992). The frequency measure being unreliable would mean that the results would be meaningless, and that no inference could be made confidently about the effect of fatigue on these muscles. Despite this, the results from the amplitude and temporal measures indicate that there was fatigue present in the lower trapezius. Perhaps median frequency is in fact a valid measure for this muscle particularly, which might be due to the relatively small degree of length change during the measurement task. Dissimilar physiological properties of the AD and LT would also support median frequency being more appropriate in the latter than the former, with the AD able to move through a greater range of length in fibres. A greater degree of muscle fibre lengthening results in smaller fibre diameter, which changes conduction velocity (Arendt-Nielsen et al., 1992). Conduction velocity in turn affects frequency measures so these outcomes may not be appropriate in muscles that have a high degree of shortening and lengthening, such as the AD.

5.4 Time to peak

Based on findings in previous research (Cools et al, 2002), the current study hypothesised that the time to peak muscle amplitude would be delayed following the intervention. Cools et al (2002) cited reductions in motor neuron firing rates and impaired conduction velocity as the reason for delays in onset time found in the shoulder muscles. The same mechanisms would also result in delays in peak muscle amplitude. However, this hypothesis was not supported by the present study's findings, which identified earlier peaks in both the MT and LT after the repeat spiking bout.

Previous research (Cools et al, 2002) examined the effects of fatigue in an reactionary arm-drop movement. This work found that shoulder fatigue resulted in an increased latency in the involuntary motor response of the shoulder muscles. One may think that increased latency due to fatigue would also mean delayed voluntary activation of the muscles, and as a result, delayed peak amplitude. However, results from the present study demonstrate that this is not the case. Therefore, it seems that fatigue-induced changes in an involuntary muscle response cannot be extrapolated to voluntary muscle action in the shoulder musculature.

The fact that the trapezius muscles displayed no change in amplitude, but did display a reduction in peak time indicates that there are changes occurring in the motor control of the arm raising task. Alterations in mechanics in order to prioritise a desired outcome may explain the observed changes in muscle behaviour in the present study. Skilled athletes maintain a desired outcome during movement (such as strength or velocity outputs), even in the presence of fatigue. In the current study, subjects were instructed to “raise the arm as fast as possible”, and so the objective of the task was to maintain maximum velocity in the arm-raise. Various theories have been proposed as to how athletes achieve a desired outcome in a task, even in the face of an intervention.

The *critical force theory* suggests that there is a certain 'critical' magnitude of force that must be reached in order to achieve a desired outcome. Biomechanical principles dictate that to generate maximum velocity of the arm, there is a certain amount of torque associated, which requires a certain force from the muscles around the joint. Moreover, this torque is consistent in both pre and post-intervention states, since the mass of the arm, nor the axes of rotation change. However, in the present study, the reductions in peak amplitude and area under the curve (Table 3) indicate that the force producing capacity of the prime mover (anterior deltoid) is impaired due to fatigue following the intervention. Consequently, the motor control system is not as readily able to produce the required torque for maximum velocity and must find a solution.

Critical force theory would suggest that, in the presence of the intervention, the system self-organises in whatever way necessary to produce the torque required for maximum velocity. It might be that, due to the presence of fatigue in the anterior deltoid, the trapezius muscles activate earlier to maintain the desired critical force around the shoulder joint as a whole.

In rapid arm-raising tasks, anticipatory postural adjustments (APA's) occur in the muscles of both the trunk and lower limbs (Strang & Berg, 2007). In the present study, the earlier peak of the mid and lower trapezius muscles observed in the post-intervention condition may be due to these muscles acting as an anticipatory postural adjustment (Ferretti, Papandrea, Conteduca, & Mariani) mechanism to provide sufficient stability to the system. APA's are simply the execution of the early motor plan as part of the voluntary motor system, which acts anticipatorily to maintain system equilibrium in the face of internal or external threats to stability (Bouisset, Richardson & Zattara, 2000). It is entirely plausible that similar anticipatory activation/motor planning may occur in the scapulothoracic muscles, during rapid arm raise tasks, to enhance the stability of the shoulder girdle ahead of the mechanical disturbance.

The proposed APA role of the trapezius is supported by the changed order of peak activation in the pre and post intervention conditions, with the trapezius muscles' peaks occurring after that of the deltoid in the pre-condition, and prior to it in the post condition. This would indicate that the trapezius is stabilising the shoulder girdle in preparation for the action of the deltoid causing a disturbance to the system. Moreover, the trapezius muscles peaks occurring prior to the deltoid's may be because these muscles also activate (muscle onset) earlier than the deltoid. However this study did not examine onsets, and in order to truly ascertain as to whether the observed results are due to an APA mechanism, onset times should be a particular area of focus for future studies. A further recommendation for future work is to include strength outcome measures to investigate the force production capacity of the system as a whole before and after the intervention. This may shed light on whether changes in the system are facilitating a critical force to achieve the desired maximum velocity of the arm during movement.

5.5 Rank order

The order of muscle amplitude peaks were affected by the intervention in this study. Current literature documents that activation patterns of scapula muscles are consistent regardless of fatigue or injury, therefore it was hypothesised that the same rank order would be present in both pre and post measurements in the current study. This was not the case, with the rank order of peaks in the pre condition, from earliest to latest, being AD, SA, UT, LT, MT. The rank order of the peaks changed in the post measurement to LT, MT, UT, AD, SA. However, the rank order is not necessarily a reliable indicator of the coordination pattern of these muscles, since no analysis was performed to determine the significance of the ranking. Moreover multiple researchers have noted the high degree of variability in temporal muscle outcomes (Cools et al., 2002; Moraes et al., 2008; Wadsworth & Bullock-Saxton, 1997). Therefore the rank order of peaks being determined by means may not be the most informative measure. To that point, the changes in mean rank were analysed on an individual level, with significant changes in mean rank being observed in two muscles, the MT and SA.

Changes in the MT peak time may not be of much practical significance, when considering the context of the observed change. Figure 11 shows that the condition in which the mean rank of the MT peak changed significantly was in the pre measurement, which was higher than both the control, and the post measurement. Due to the high reliability of the measures in this study, the MT rank differing in the control and pre-intervention condition is not to be expected, thus is possibly a systematic error, rather than a reflection of a true change between the two measurements. Regardless of the implications of this result, it may explain the change in SA peak ranking observed in the post condition. As evidenced by the results of time to peak (TTP) mean difference, decreases in the TTP of the MT and LT were present, which would bring the ranking of those muscles higher relative to the SA (i.e. peaking earlier), since the SA's peak time remains constant (reflected by the insignificant TTP result for this muscle). If these changes are consistent over multiple occasions, the mean rank of the SA decreases, despite it's peak time not changing. Functionally, this is meaningful due to the integrated roles of the MT, LT and SA in scapula motion. Earlier peak timing of LT in particular may be a compensatory mechanism for compromised SA force production.

Although the results of the present study do not indicate any significant effects of the intervention in the SA, there still may be changes. For example the change in TTP of the SA is non-significant but appears there may be a trend towards an increase, which would require the earlier activation of MT and LT to facilitate upward rotation.

There is limited research regarding peak amplitude sequencing at present. Only one study was found, in which peak amplitude sequencing in healthy participants during an arm abduction movement was found to be MT, UT, SA, LT (Wickham, Pizzari, Stansfeld, Burnside, & Watson, 2009). The differing order suggests that the results are not comparable to the present study, which can be explained by the different measurement tasks. With limited sources to compare the present study to, the results of the TTP rank order are compared to other studies examining rank order of onset times found in literature. Cools et al. have researched patterns of activation during an arm raising task – both fatigued and non-fatigued participants demonstrated the sequence from earliest to latest as UT, MT, LT, although these were non-significant . The same sequence was observed in subjects with SIS also. This study did not include the SA, however the order of the trapezius muscles alone differs from that observed in the present study. Researchers (Kibler, Chandler, Shapiro, & Conuel, 2007) have found that order of muscles during early 'cocking' phase of the tennis serve was SA, UT, LT, whereas

Both Moraes and Wadsworth documented similar recruitment patterns of UT, SA, MT, LT healthy and SIS subjects. Also, De Mey (De Mey, Danneels, Cagnie, & Cools, 2012) revealed a pattern of SA activating significantly earlier than the trapezius muscles, which activated simultaneously. These studies differ, such that it would seem there is no consistent pattern of muscle activation. However a common theme is early onset of the SA, which was observed in the TTP measures in the pre-intervention condition in present study. This indicates a possible link between onset and peak amplitude timing, although requires more thorough investigation. Moreover, the different order of muscle onsets in the studies may simply be a reflection of the different methods used, and slight deviations in assessment task eliciting different joint angles, and therefore muscle activations. In summary, the results of the present study indicate that repetitive spiking has an effect on the sequencing of peak muscle amplitudes, although the reasons for this are unclear. The present literature is insufficient to draw conclusions about why this effect was observed, and as such requires more extensive investigation.

5.6 Time broadness

Time broadness was found to be unchanged as a result of the spiking intervention in this experiment, not supporting the hypothesis. A lack of studies were found that examined time broadness in fatigued states, so limited inference can be made about this result. As discussed in the previous section, the large variability may play a role in the lack of results observed. The calculation of time broadness incorporates the highly variability associated with the temporal measure of each individual muscle. This is reflected in the confidence interval for the mean difference in pre-post scores for this variable, which is outside the bounds of possible difference based on the context. High variability might have led to the inability to detect a consistent activation pattern in both pre and post measures.

Readers are encouraged to consider how this result fits in the wider literature. It is difficult to predict whether time broadness is affected by fatigue or not. While the present study did consider the time to peaks of each muscle, which suggest that time broadness should have displayed changes as a result of the intervention, the study did not analyse how the duration of the movement cycle changed with fatigue. Reductions in TTP observed in two of four muscles would reduce the time broadness, assuming the total time of the movement cycle was constant. However, since the duration of the movement cycle was not included in the analysis, comment cannot be made as to whether this was the case.

5.7 Future research directions

This thesis builds upon existing literature around the behaviour of the scapula muscles, and has applied this to volleyball athletes specifically. However, a large portion of the current research considers the variable of muscle onset time, which the authors decided not to investigate in the current study. This decision was made due to the difficulty extracting this variable as a result of poor reliability and high variability. Onset time may be an important variable to investigate in future research. The present study considered time to peak and time broadness as temporal measures, and the results indicated fatigue affected these outcomes. Coupled with the temporal variables examined in this research, investigating onset time would give greater understanding of the overall function of the muscles and the effect of fatigue on the motor control pattern. Moreover, no research was able to be found that considers onset time in volleyball populations, highlighting a need.

Literature is still unclear as to how changes in muscle outcomes are linked to fatigue and shoulder pathologies. Longitudinal studies that track shoulder muscle outcomes over the course of a playing season, or ideally multiple seasons, would be better suited to reveal the potential causal or consequential nature of fatigue and injury. This would be particularly ideal with respect to SIS, since such shoulder injuries in overhead athletes usually develop over long periods of time. Similarly, a study that was able to examine the effects of game or training-induced fatigue would provide more context on the relationship between fatigue and scapula muscle function. Inclusion of pre and post fatiguing strength testing may be of use, and would be non-invasive and practical to implement by using a handheld dynamometer.

Understanding the effects of fatigue on the scapula rotators will provide practitioners with a direction for implementing training/rehabilitative programmes to ensure optimal function for athletes. It has been hypothesised that such intervention could alter muscle outcomes, although De Mey et al (De Mey et al., 2012) found no change in onset times during arm raising as a result of a 6 week resistance training program. This is an area that requires further investigation, with limited literature currently in publication.

5.8 Limitations

The main limitations of this study are presented in this section. In particular, these are associated with the ecological validity, the presence of fatigue, participant recruitment and sample size, and difficulties in collecting EMG data.

Ecological validity of the fatiguing protocol was a limitation of this research. The standing spiking procedure performed as fast as possible in this study is not representative of the time- demands of actions in a real volleyball match or training. The constraints of the fatiguing protocol were justified because it allowed the procedure to be standardised across participants. Furthermore, it would have also been more time consuming to have the subject ready themselves between balls being set or tossed in to the air. Therefore, it was decided the 'standing spike' task, would allow for a greater level of exertion to be achieved.

The level of participants' exertion was another limitation found in this thesis. RPE has repeatedly been investigated and proved to be a good indicator of fatigue in the literature, although still relies on honest reporting. In particular, the subjective reporting of RPE means that subjects may not have been exerting themselves as hard as they reported to be. From observation, it seemed that true maximal exertion and pace during the spiking task was not reached by some subjects – which may have been a result of the unfamiliar situation, or simply lack of motivation. Incorporating the fatiguing protocol as part of a training session may increase the level of "buy-in" from participants and help to achieve greater output from athletes.

Due to the scarcity of high-level volleyball players in the area, a sample of convenience was selected. As such, a small sample size was used in the study. While the number of subjects exceed the number determined *a priori* using by a power calculation, the calculation was based on a previously reported effect size for one variable (frequency of the LT). This may not have ensured enough power for all variables in the analysis. If different outcome measures do not display the same magnitude of response to an intervention, the effect size will differ. Power was unable to be calculated for other outcome measures in the analysis, due to the lack of reported effect sizes existing in similar literature. This is also a caveat of the unique design of the present study. The combination of measurement task, muscles examined, and athletic population was unique, therefore calculating power from an effect size reported in a dissimilar study would not have been appropriate.

There were limitations to the process of EMG data collection which resulted in difficulty analysing the data. Firstly, the timing of the instructions given to the subjects was consistent and therefore became predictable. The *"ready"* call prior to the arm raise movement occurred just a second or two prior to the audible start cue. This might have invoked tension in the muscles and/or early movement in anticipation of the cue and could be an explanation for the erroneous baseline observed in some trials. This timing effect may have been exaggerated from trial to trial, whereby the subjects may have become increasingly aware that the start cue would be coming very shortly after the *"ready"* call. Nonetheless, there were still an acceptable number of ‘good’ trials achieved which meant this did not affect the analysis. Future work using a movement cue should randomise the length of time between the preparatory instruction and the movement trigger.

6 Conclusion

This study has shown that an acute bout of repetitive spiking does elicit changes in scapulothoracic muscle activation in volleyball athletes. The results also help answer the question identified in the literature – whether altered muscle behaviour is a precursor to injury, or a result of it. The spiking intervention was shown to affect peak amplitude, area under the EMG curve, frequency and time to peak. Contrasting results were observed in the AD and the LT area under the curve. Due to their differing role in spiking, this result supports the theory that the effects of muscular fatigue are context dependent, and differ based on factors such as contraction type, and the degree of muscle fibre lengthening. An explanation for these results is that the system acts to maintain stability of the shoulder girdle during rapid tasks, and the authors propose that anticipatory postural adjustments occur in the scapulothoracic muscles to achieve this.

The LT displayed significant differences for three of four outcome measures: area under the EMG curve, frequency, and time to peak. This highlights that LT is definitely susceptible to fatigue caused by repetitive spiking. Players, coaches and training staff should be aware of this, and may give particular attention in injury prevention/rehabilitation programs. All included participants were free of any shoulder injury for at least one year at the time of the study. The fact that significant changes in muscle function were observed in this uninjured state, suggest that altered muscle activation of the scapulothoaracic muscles are in fact a precursor to shoulder overuse injuries, in particular SIS.

References

Bhat, N., & Balamurugan, K. (2017). Injuries among varsity men volleyball players. *International Journal of Physical Education, Sports and Health, 4*(3), 68-71.

Bradley, J. P., & Tibone, J. E. (1991). Electromyographic analysis of muscle action about the shoulder. *Clin Sports Med, 10*(4), 789-805.

Bouisset, S., Richardson, J., & Zattara, M. (2000). Do anticipatory postural adjustments occurring in different segments of the postural chain follow the same organisational rule for different task movement velocities, independently of the inertial load value? *Experimental Brain Research, 132*(1), 79-86.

Cairns, P. S., Knicker, J. A., Thompson, W. M., & Sjøgaard, W. G. (2005). Evaluation of Models Used to Study Neuromuscular Fatigue. *Exercise and Sport Sciences Reviews, 33*(1), 9-16.

Castelein, B., Cagnie, B., Parlevliet, T., & Cools, A. (2016). Scapulothoracic muscle activity during elevation exercises measured with surface and fine wire EMG: A comparative study between patients with subacromial impingement syndrome and healthy controls. *Manual Therapy*, *23*, 33-39.

Castelein, B., Cagnie, B., Parlevliet, T., Danneels, L., & Cools, A. (2015). Optimal Normalization Tests for Muscle Activation of the Levator Scapulae, Pectoralis Minor, and Rhomboid Major: An Electromyography Study Using Maximum Voluntary Isometric Contractions. *Archives of Physical Medicine and Rehabilitation*, *96*(10), 1820-1827.

Chaffin, D. B. (1973). Localized muscle fatigue--definiton and measurement. *Journal of Occupational Medicine 15*(4), 346.

Challoumas, D., Stavrou, A., & Dimitrakakis, G. (2017). The volleyball athlete's shoulder: biomechanical adaptations and injury associations. *Sports Biomechanics*, *16*(2), 220-237.

Clarsen, B., Myklebust, G., & Bahr, R. (2013). Development and validation of a new method for the registration of overuse injuries in sports injury epidemiology: the Oslo Sports Trauma Research Centre (OSTRC) Overuse Injury Questionnaire. *British Journal of Sports Medicine*, *47*(8), 495.

Cools, A. M., Johansson, F. R., Borms, D., & Maenhout, A. (2015). Prevention of shoulder injuries in overhead athletes: a science-based approach. *Brazilian Journal of Physical Therapy*, *19*(5), 331-339.

Cools, A. M., Witvrouw, E. E., De Clercq, G. A., Danneels, L. A., & Cambier, D. C. (2003). Scapular muscle recruitment patterns: trapezius muscle latency with and without impingement symptoms. *The American Journal of Sports Medicine, 31*(4), 542.

Cools, A. M., Witvrouw, E. E., De Clercq, G. A., Danneels, L. A., Willems, T. M., Cambier, D. C., & Voight, M. L. (2002). Scapular muscle recruitment pattern: electromyographic response of the trapezius muscle to sudden shoulder movement before and after a fatiguing exercise. *The Journal of Orthopaedic and Sports Physical Therapy, 32*(5), 221-229.

Davis, M. P., & Walsh, D. (2010). Mechanisms of fatigue. *Journal of Supportive Oncology, 8*(4), 164-174.

De Mey, K., Danneels, L., Cagnie, B., & Cools, A. M. (2012). Scapular muscle rehabilitation exercises in overhead athletes with impingement symptoms: effect of a 6-Week training program on muscle recruitment and functional outcome. *The American Journal of Sports Medicine, 40*(8), 1906-1915.

Edwards, S. L., Bell, J., & Bigliani, L. U. (2009). Subacromial Impingement. *The Athlete's Shoulder*, New York: Churchill Livingstone.

Enoka, R. M., & Duchateau, J. (2008). Muscle fatigue: what, why and how it influences muscle function. *Journal of Physiology, 586*(1), 11-23.

Eom, H. J., & Schutz, R. W. (1992). Statistical analyses of volleyball team performance. *Research Quarterly for Exercise and Sport, 63*(1), 11-18.

Erickson, B. J., Sgori, T., Chalmers, P. N., Vignona, P., Lesniak, M., Bush-Joseph, C. A., Verma, N. N. & Romeo, A. A. (2016). The impact of fatigue on baseball pitching mechanics in adolescent male pitchers. *Arthroscopy: The Journal of Arthroscopic & Related Surgery, 32*(5), 762-771.

Escamilla, R., & Andrews, J. (2009). Shoulder Muscle Recruitment Patterns and Related Biomechanics during Upper Extremity Sports. *Sports Medicine, 39*(7), 569-590.

Fares, M. Y., Salhab, H. A., Khachfe, H. H., Kane, L., Fares, Y., Fares, J., & Abboud, J. A. (2020). Upper limb injuries in Major League Baseball. *Physical Therapy in Sport, 41*, 49-54.

Faulkner, J. A., Brooks, S. V., & Zerba, E. (1995). Muscle atrophy and weakness with aging: contraction-induced injury as an underlying mechanism. *The Journals of Gerontology, 50*, 124-129.

Ferretti, A., Papandrea, P., Conteduca, F., & Mariani, P. P. (1992). Knee ligament injuries in volleyball players. *The American Journal of Sports Medicine, 20*(2), 203-207.

Fleisig, G. S., Andrews, J. R., Dillman, C. J., & Escamilla, R. F. (1995). Kinetics of baseball pitching with implications about injury mechanisms. *The American Journal of Sports Medicine, 23*(2), 233-239.

Forthomme, B., Croisier, J.-L., Ciccarone, G., Crielaard, J.-M., & Cloes, M. (2005). Factors correlated with volleyball spike velocity. *The American Journal of Sports Medicine*, *33*(10), 1513-1519.

Frisch, K. E., Clark, J., Hanson, C., Fagerness, C., Conway, A., & Hoogendoorn, L. (2017). High prevalence of nontraumatic shoulder pain in a regional sample of female high school volleyball athletes. *Orthopaedic Journal of Sports Medicine, 5*(6).

Gabriel, A. D., Basford, R. J., & An, R. K.-N. (2001). Neural adaptations to fatigue: implications for muscle strength and training. *Medicine and Science in Sports and Exercise, 33*(8), 1354-1360.

Gandevia, S. C. (2001, 2001/10//). Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews, 81(4),* 1725.

Gerdle, B., Larsson, B., & Karlsson, S. (2000). Criterion validation of surface EMG variables as fatigue indicators using peak torque: a study of repetitive maximum isokinetic knee extensions. *Journal of Electromyography and Kinesiology*, *10*(4), 225-232.

Hermens, H. J., Freriks, B., Merletti, R., Stegeman, D., Blok, J., Rau, G., & Hägg, G. (1999). European recommendations for surface electromyography.

Hirashima, M., Kadota, H., Sakurai, S., Kudo, K., & Ohtsuki, T. (2002). Sequential muscle activity and its functional role in the upper extremity and trunk during overarm throwing. *Journal of Sports Sciences, 20*(4), 301-310.

Hodges, P. W. & Bui, B. H. (1996). A comparison of computer-based methods for the determination of onset of muscle contraction using electromyography. *Electromyography and Motor Control, 101*(6), 511-519.

Illyés, A., & Kiss, R. M. (2007). Electromyographic analysis in patients with multidirectional shoulder instability during pull, forward punch, elevation and overhead throw. *Knee Surgery, Sports Traumatology, Arthroscopy, 15*(5), 624-631.

Inman, V. T., Saunders, J. D. M., & Abbott, L. C. (1944). Observations on the function of the shoulder joint. *Journal of Bone & Joint Surgery*, *26*(1), 1-30.

Jacobson, R. P., & Benson, C. J. (2001). Amateur volleyball attackers competing despite shoulder pain: analysis of play habits, anthropometric data, and specific pathologies. *Physical Therapy in Sport, 2*(3), 112-122.

Jensen, B. R., Pilegaard, M., & Sjøgaard, G. (2000). Motor unit recruitment and rate coding in response to fatiguing shoulder abductions and subsequent recovery. *European Journal of Applied Physiology, 83*(2-3), 190-199.

Kaminski, T. W., & Royer, T. D. (2005). Electromyography and Muscle Force: Caution Ahead. *Athletic therapy today, 10*(4), 43-45.

Katakura, M., Duffell, L. D., Strutton, P. H., & McGregor, A. H. (2011). Effects of a 60~second maximum voluntary isometric contraction on torque production and EMG output of the quadriceps muscle group. *Isokinetics and Exercise Science, 19*(1), 13-22.

Kennedy, J. C., & Hawkins, R. J. (1980). Impingement syndrome in athletes. *The American Journal of Sports Medicine, 8*(3), 151-158.

Khal, K. M., Moore, S. D., Pryor, J. L., & Singh, B. (2020). Changes in infraspinatus and lower trapezius activation in volleyball players following repetitive serves. *International Journal of Sports Physical Therapy, 15*(2), 196-202.

Kibler W. B. The Role of the Scapula in Athletic Shoulder Function. The American Journal of Sports Medicine. 1998;26(2):325-337.

Kibler, W. B., Chandler, T. J., Shapiro, R., & Conuel, M. (2007). Muscle activation in coupled scapulohumeral motions in the high performance tennis serve. *British Journal of Sports Medicine, 41*(11), 745-791.

Kilic, O., Maas, M., Verhagen, E., Zwerver, J., & Gouttebarge, V. (2017). Incidence, aetiology and prevention of musculoskeletal injuries in volleyball: A systematic review of the literature. *European Journal of Sport Science, 17*(6), 765-793. doi:10.1080/17461391.2017.1306114

Klich, S., Kawczyński, A., Pietraszewski, B., Zago, M., Chen, A., Smoter, M., . . . Lovecchio, N. (2021). Electromyographic Evaluation of the Shoulder Muscle after a Fatiguing Isokinetic Protocol in Recreational Overhead Athletes. *International journal of environmental research and public health, 18*(5), 2516. doi:10.3390/ijerph18052516

Konrad, P. (2005). The ABC of EMG. *A Practical Introduction to Kinesiological Electromyography, 1*(2005), 30-35.

Kugler, A., Krüger-Franke, M., Reininger, S., Trouillier, H. H., & Rosemeyer, B. (1996). Muscular imbalance and shoulder pain in volleyball attackers. *British Journal of Sports Medicine, 30*(3), 256-259.

Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, 159-174.

Leadbetter, W. B. (1992). Cell-matrix response in tendon injury. *Clinics in Sports Medicine, 11*(3), 533-578.

Li, X., Zhou, H., Williams, P., Steele, J. J., Nguyen, J., Jäger, M., & Coleman, S. (2013). The epidemiology of single season musculoskeletal injuries in professional baseball. *Orthopedic Reviews*, *5*(1).

Lombardi Jr, I., Magri, Â. G., Fleury, A. M., Da Silva, A. C., & Natour, J. (2008). Progressive resistance training in patients with shoulder impingement syndrome: A randomized controlled trial. *Arthritis Care & Research, 59*(5), 615-622.

Ludewig, P. M., & Cook, T. M. (2000). Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. *Physical Therapy, 80*(3), 276-291.

Maunder, E., Kilding, A. E., & Cairns, S. P. (2017). Do Fast Bowlers Fatigue in Cricket? A paradox between player anecdotes and quantitative evidence. *International Journal of Sports Physiology & Performance, 12*(6), 719-727.

McQuade, K., Dawson, J., & Smidt, G. (1998). Scapulothoracic muscle fatigue associated with alterations in scapulohumeral rhythm kinematics during maximum resistive shoulder elevation. *The Journal of orthopaedic and sports physical therapy, 28*(2), 74.

McQuade, K., Wei, S., & Smidt, G. (1995). Effects of local muscle fatigue on three-dimensional scapulohumeral rhythm. *Clinical Biomechanics, 10*(3), 144-148.

Mitchinson, L., Campbell, A., Oldmeadow, D., Gibson, W., & Hopper, D. (2013). Comparison of upper arm kinematics during a volleyball spike between players with and without a history of shoulder injury. *Journal of applied biomechanics, 29*(2), 155-164.

Moraes, G. F. S., Faria, C. D. C. M., & Teixeira-Salmela, L. F. (2008). Scapular muscle recruitment patterns and isokinetic strength ratios of the shoulder rotator muscles in individuals with and without impingement syndrome. *Journal of Shoulder and Elbow Surgery, 17*(1), S48-S53.

Mullaney, M. J., McHugh, M. P., Donofrio, T. M., & Nicholas, S. J. (2005). Upper and lower extremity muscle fatigue after a baseball pitching performance. *American Journal of Sports Medicine, 33*(1), 108-113.

Nuño, A., Chirosa Ignacio, J., van Den Tillaar, R., Guisado, R., Martín, I., Martinez, I., & Chirosa Luis, J. (2016). Effects of fatigue on throwing performance in experienced team handball players. *Journal of Human Kinetics*, *54*(1), 103-113.

Oberg, T., Sandsjo, L., & Kadefors, S. (1990). Electromyogram mean power frequency in non-fatigued trapezius muscle. *European Journal of Applied Physiology*, *61*(1), 362-369.

Oliveira, L. d. S., Moura, T. B. M. A., Rodacki, A. L. F., Tilp, M., & Okazaki, V. H. A. (2020). A systematic review of volleyball spike kinematics: Implications for practice and research. *International Journal of Sports Science & Coaching*, *15*(2), 239-255.

Phadke, V., Camargo, P., & Ludewig, P. (2009). Scapular and rotator cuff muscle activity during arm elevation: a review of normal function and alterations with shoulder impingement. *Brazilian Journal of Physical Therapy*, *13*(1), 1-9.

Plawinski, M. (2008). An analysis of the different spike attack arm swings used in elite levels of men's volleyball. (Master's Thesis, Queen's Univeristy, Ontario, Canada). Available from ProQuest Dissertations & Theses Global database. (UMI No. MR46247).

Purves, D. (2001). *Neuroscience* (2nd edition. ed.). Sunderland, Mass.: Sinauer Associates.

Reeser, J., Fleisig, G., Bolt, B., & Ruan, M. (2010). Upper limb biomechanics during the volleyball serve and spike. *Sports Health: A Multidisciplinary Approach, 2*(5), 368-374.

Reeser, J., Joy, E., Porucznik, C., Berg, R., Colliver, E., & Willick, S. (2010). Risk factors for volleyball-related shoulder pain and dysfunction. *Physical Medicine and Rehabilitation, 2*(1), 27-36.

Reinold, M. M., Wilk, K. E., Macrina, L. C., Sheheane, C., Dun, S., Fleisig, G. S., Crenshaw, K., & Andrews, J. R. (2008). Changes in shoulder and elbow passive range of motion after pitching in professional baseball players. *The American Journal of Sports Medicine, 36*(3), 523-527.

Renshaw, D., Bice, M. R., Cassidy, C., Eldridge, J. A., & Powell, D. W. (2010). A comparison of three computer-based methods used to determine EMG Signal Amplitude. *International Journal of Exercise Science, 3*(1), 43-48.

Rokito, A. S., Jobe, F. W., Pink, M. M., Perry, J., & Brault, J. (1998). Electromyographic analysis of shoulder function during the volleyball serve and spike. *Journal of Shoulder and Elbow Surgery, 7*(3), 256-263.

Roy, J.-S., Moffet, H., & McFadyen, B. J. (2008). Upper limb motor strategies in persons with and without shoulder impingement syndrome across different speeds of movement. *Clinical Biomechanics, 23*(10), 1227-1236.

Santos, M. J., Belangero, W. D., & Almeida, G. L. (2007). The effect of joint instability on latency and recruitment order of the shoulder muscles. *Journal of Electromyography and Kinesiology, 17*(2), 167-175.

Sardinha, L. B., & Zebas, C. J. (1986). *The Effect of Perceived Fatigue on Volleyball Spike Skill Performance.* Paper presented at the ISBS-Conference Proceedings Archive.

Seitz, A. L., & Uhl, T. L. (2012). Reliability and minimal detectable change in scapulothoracic neuromuscular activity. *Journal of Electromyography and Kinesiology, 22*(6), 968-974.

Seminati, E., Marzari, A., Vacondio, O., & Minetti, A. E. (2015). Shoulder 3D range of motion and humerus rotation in two volleyball spike techniques: injury prevention and performance. *Sports Biomechanics, 14*(2), 216-231.

Seminati, E., & Minetti, A. E. (2013). Overuse in volleyball training/practice: A review on shoulder and spine-related injuries. *European Journal of Sport Science, 13*(6), 732-743.

Serrien, B., Goossens, M., & Baeyens, J.-P. (2018). Proximal-to-Distal Sequencing and Coordination Variability in the Volleyball Spike of

Elite Youth Players: Effects of Gender and Growth. *Journal of Motor Learning and Development*, *6*(2), 250-266.

Serrien, B., Ooijen, J., Goossens, M., & Baeyens, J.-P. (2016). A motion analysis in the volleyball spike–part 1: three dimensional kinematics and performance. *International Journal of Human Movement and Sports Science*, *4*(4), 70-82.

Struyf, F., Cagnie, B., Cools, A., Baert, I., Brempt, J. V., Struyf, P., & Meeus, M. (2014). Scapulothoracic muscle activity and recruitment timing in patients with shoulder impingement symptoms and glenohumeral instability. *Journal of Electromyography and Kinesiology*, *24*(2), 277-284.

Taylor, J. L., Amann, M., Duchateau, J., Meeusen, R., & Rice, C. L. (2016). Neural Contributions to Muscle Fatigue: From the Brain to the Muscle and Back Again. *Medicine and Science in Sports and Exercise*, *48*(11), 2294-2306.

Tschoepe, B. A., Sherwood, D. E., & Wallace, S. A. (1994). Localized muscular fatigue duration, EMG parameters and accuracy of rapid limb movements. *Journal of Electromyography and Kinesiology*, *4*(4), 218-229.

Verhagen, E. A. L. M., Van Der Beek, A. J., Bouter, L. M., Bahr, R. M., & Mechelen, W. V. (2004). A one season prospective cohort study of volleyball injuries. *British Journal of Sports Medicine, 38*(4), 477.

Wadsworth, D. J., & Bullock-Saxton, J. E. (1997). Recruitment patterns of the scapular rotator muscles in freestyle swimmers with subacromial impingement. *International Journal of Sports Medicine, 18*(8), 618-624.

Wang, H. K., & Cochrane, T. (2001a). A descriptive epidemiological study of shoulder injury in top level English male volleyball players. *International Journal of Sports Medicine, 22*(02), 159-163.

Wang, H. K., & Cochrane, T. (2001b). Mobility impairment, muscle imbalance, muscle weakness, scapular asymmetry and shoulder injury in elite volleyball athletes. *The Journal of Sports Medicine and Physical Fitness, 41*(3), 403-410.

Wickham, J., Pizzari, T., Stansfeld, K., Burnside, A., & Watson, L. (2009). Quantifying 'normal' shoulder muscle activity during abduction. *Journal of Electromyography and Kinesiology, 20*(2), 212-222.

Wilk, K. E., Andrews, J. R., Cain, E. L., & Devine, K. (2009). CHAPTER 33 - Shoulder Injuries in Baseball. In K. E. Wilk, M. M. Reinold, & J. R. Andrews (Eds.), *The Athlete's Shoulder (Second Edition)* (pp. 401-420). Philadelphia: Churchill Livingstone.

Wilk, K. E., Meister, K., & Andrews, J. R. (2002). Current Concepts in the Rehabilitation of the Overhead Throwing Athlete. *The American Journal of Sports Medicine, 30*(1), 136-151.

Windt, J., & Gabbett, T. J. (2017). How do training and competition workloads relate to injury? The workload—injury aetiology model. *British Journal of Sports Medicine, 51*(5), 428-435.

Yaghoubi, M., Esfehani, M. M., Hosseini, H. A., Alikhajeh, Y., & Shultz, S. P. (2015). Comparative electromyography analysis of the upper extremity between inexperienced and elite water polo players during an overhead shot. *Journal of Applied Biomechanics, 31*(2), 79-87.

Yoon, T., Schlinder Delap, B., Griffith, E. E., & Hunter, S. K. (2007). Mechanisms of fatigue differ after low- and high-force fatiguing contractions in men and women. *Muscle Nerve, 36*(4), 515-524.

Zandi, S., Rajabi, R., Mohseni-Bandpei, M., & Minoonejad, H. (2018). Electromyographic Analysis of Shoulder Girdle Muscles in Volleyball Throw: A Reliability Study. *Biomedical Human Kinetics, 10*(1), 141-149.

Appendices

Appendix A – 15 Point Borg RPE scale

6	No exertion
7	
8	
9	
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	
20	Maximal exertion

Appendix B – demographic questionnaire for subjects

Participant information sheet:

Age:
Gender:
Height:
Mass:
Hitting arm:
Playing position:
Number of years playing:
Previous injury history (in the past 12 months):

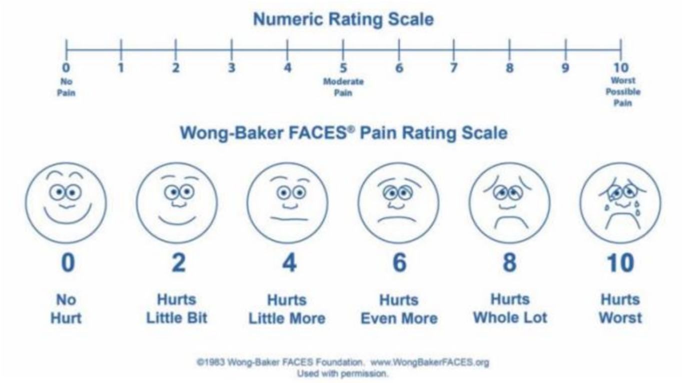
- *Have you been diagnosed with subacromial impingement syndrome?*

- *Experienced numbness or pain in the shoulder during playing volleyball?*

- *Missed playing time due to shoulder injury/pain?*

<u>Pain questionnaire (numerical scale)</u>

On the following scale, rate any shoulder pain while playing volleyball currently:



<u>Clinical tests</u>

Hawkins test result: POSITIVE/NEGATIVE

Jobe (empty can) test result: POSITIVE/NEGATIVE