ANALYSIS OF SCAPULOTHORACIC
MUSCLE RECRUITMENT IN OVERHEAD
ATHLETES

Ann Cools

Thesis submitted in fulfilment of the requirements for the degree of Doctor in Motor Rehabilitation and Physiotherapy

Ghent 2003
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Ann Cools
Ghent, June 26th 2003
CHAPTER 1

GENERAL INTRODUCTION
GENERAL INTRODUCTION

Chronic shoulder pain is probably the most common upper extremity problem in recreational, competitive and elite athletes. Injury from throwing can occur to any structure contributing to the dynamic or static restraint of the shoulder. Two common aetiologies of shoulder pain are shoulder instability and shoulder impingement. In the young, athletic population these clinical entities are often interrelated. The term impingement was introduced by Neer, referring to a condition with a pattern of signs and symptoms consistent with some form of subacromial space outlet obstruction irritating the supraspinatus tendon. Neer further defines the stages of impingement that follow a pattern of severity. Most of Neer’s work, however, was based on observations in older, non-athletic patients. Many authors now feel that impingement-type pain can be divided into two general categories, based on the age and occupation of the patient. The pathological mechanisms in older patients are usually the consequence of the aging process and in some manner compromise the subacromial space. These pathological processes are often referred to as primary external subacromial impingement. In the younger population the patient most commonly is an overhead athlete in whom repetitive throwing motions can result in repeated microtraumata involving the stabilising mechanisms of the glenohumeral joint. This minor instability can lead to anterior subluxation of the humeral head. Recurrent subluxations may then result in a secondary impingement phenomenon involving the rotator cuff and biceps tendon. This secondary impingement is the consequence of relative functional narrowing of the subacromial space during overhead activities. This continuum of progressive shoulder pathology has been
termed the “instability complex” or “functional shoulder instability”, and can be defined as activity-related symptoms, with or without detectable shoulder laxity.

More recently, a form of impingement (internal or superior glenoid impingement) has been identified which differs from the impingement of the acromion on the rotator cuff tendons. Internal or superior glenoid impingement occurs during the late cocking stage of throwing when the undersurface of the rotator cuff is impinged against the postero-superior surface of the glenoid. It is thought that repetitive stresses to some extent may result in microtraumata to the glenohumeral ligaments and capsule. Attenuation of the static stabilisers induces a mild instability pattern and increases the demands on the dynamic stabilisers, the rotator cuff. This may lead to a vicious circle causing fatigue and stretching of the rotator cuff muscles allowing the humeral head to move anteriorly and superiorly (causing secondary subacromial impingement) or allowing the greater tuberosity to impinge the rotator cuff in the posterosuperior glenoid region (causing secondary internal impingement). In addition, acquired glenohumeral internal rotation deficit, often observed in overhead athletes, may be a contributing factor to the pathomechanism of minor anterior instability and secondary impingement.

**Role of the scapula in athletic shoulder function**

The scapula plays an important role in normal shoulder function. Especially in overhead sports, where the demands on the shoulder are extremely high, the quality of movement depends on the smooth interaction between glenohumeral and scapulothoracic stability and mobility. Since the glenohumeral joint is often described as “inherently unstable” due to the
lack of passive restriction, the stability of the joint will mainly depend on the contribution of the dynamic constraints. As the glenoid fossa is the base for the glenohumeral joint and the glenohumeral stabilising muscles attach on the scapula, the performance of these dynamic stabilisers depends on the positioning and the movements of the scapula. The various roles of the scapula are concerned with achieving these motions and positions to facilitate the efficient biomechanics and thus allow optimum shoulder function. Kibler provided an accurate description of the various functions of the scapula:

The first role of the scapula is to create a stable base for the glenohumeral joint. To maintain the stable glenohumeral configuration, the scapula must move in a coordinated relationship with the moving humerus so that the instant centre of rotation – the point within the humeral head that defines the axis of rotation of the glenohumeral joint – is constrained within a physiologic pattern throughout the full range of shoulder motion during throwing or serving.

The second role of the scapula is to perform protraction and retraction movements along the thoracic wall. These movements are extremely important during the throwing motion, and primarily are controlled by the trapezius, rhomboid and serratus anterior muscles.

A third role of the scapula is to elevate the acromion. During all functional shoulder motions, elevation of the acromial arch is necessary to avoid compression of the rotator cuff tendons in the subacromial space.

The fourth role of the scapula is to provide a site for muscle attachment, as well for axioscapular as for glenohumeral muscles. The position of the scapula is important for anchoring the muscles and allowing maximal efficiency in firing of the muscles that attach to the scapula. Indirectly, the scapular position can influence glenohumeral stability. Dynamic control of scapular position and movement allows the rotator cuff muscles to function at an
optimal length and in an optimal direction to provide dynamic glenohumeral stability in all humeral positions.

Finally, the scapula functions as a link in the kinetic chain between the trunk and the upper extremity. For most shoulder movements and especially for the overhead throwing motion, the sequence of movements and forces starts at the ground in the contralateral lower limb. This sequencing is usually termed the “kinetic chain”\textsuperscript{60,61}. The scapula and the scapulothoracic muscles play a very important role in this kinetic chain, since they provide efficient generation, summation and transfer of energy from the base of support to the terminal link, usually the hand.

Maintaining functional joint stability through complementary relationships between static and dynamic restraints is the role of the sensorimotor system\textsuperscript{42,66,67,98,99,100,112}. Most assessment techniques currently available evaluate the integrity and function of sensorimotor components by measuring variables along the afferent or efferent pathways, or the final outcome of muscle activation, or a combination of these. Proprioception of the glenohumeral joint has been examined in numerous investigations\textsuperscript{1,3,12,18,48,65,67,109,110,114,115,123}. Several authors found deficits in proprioception in patients with shoulder instability\textsuperscript{48,65,110,123}. However, position sense and kinaesthesia in the scapulothoracic joint have not been examined yet. Efferent transmission can be evaluated by kinetic and kinematic measurements, electromyographic muscle activation patterns, and muscle performance characteristics. In the scapulothoracic joint, evaluation of muscle control deserves our special attention. In contrast to most other joints in the human body, the scapulothoracic joint cannot rely on strong passive stabilising structures such as a joint capsule and surrounding ligaments. Hence, scapulothoracic stability depends almost solely upon the quality and function of the dynamic contributors.
During arm motion, rotatory and translatory movements are performed by the scapula, although these movements do not occur independently of one another. Coordinated scapulothoracic and glenohumeral movements during arm elevation, known as scapulohumeral rhythm, provide a range of motion while allowing for a proper length-tension relationship between various axioscapular and glenohumeral muscles. The general scapular movement pattern consists of progressive external and upward rotation of the scapula, and movement from an anteriorly to a posteriorly tipped position as the humeral elevation angle increases. 

To produce the complex kinematics at the shoulder during humeral elevation, complementary action of scapulothoracic and glenohumeral muscles is required. Electromyographic (EMG) activity of the scapulothoracic muscles has been studied by several authors. The consensus in the literature is that upper trapezius and lower serratus anterior provide the upward rotatory force couple to produce scapular rotation during the early phase of elevation. Based on the fascicular anatomy of the trapezius muscle, Johnson et al. also hypothesized that whereas upper trapezius and serratus anterior act as prime movers around the scapula, the lower trapezius has a more stabilising role. Although the trapezius muscle is often considered a major stabilising muscle for the scapula, other scapular muscles also contribute to the stability and movement quality of the scapula. The levator scapulae and rhomboid muscles are both synergists and antagonists of the three trapezius portions. Their function is to adduct and rotate the scapula downward. Shortness of these muscles may restrict upward rotation of the acromial region, necessary for normal shoulder function.
Scapulothoracic dysfunction in the overhead athlete with shoulder pain

Several authors have suggested, based on biomechanical, physiological or clinical hypotheses, that shoulder pain in the overhead athlete may to some extent be related to scapulothoracic dysfunction. It has been thought that patients with impingement symptoms have an abnormal resting position of the scapula. These static alterations may biomechanically diminish the width of the subacromial space, and hence increase the risk of subacromial impingement. However, these assumptions have not been confirmed in experimental studies.

Changes in kinematic variables, determining scapular behaviour during arm movement, have been examined in patients with shoulder instability or impingement. The findings of these studies are consistent with clinical suggestions, regarding abnormal scapular movement patterns in patients with shoulder pain.

Based on clinical observations, muscular imbalances in the scapular muscles are often suggested in overhead athletes with shoulder pain. Most authors postulate that these imbalances are characterised by a decrease in serratus anterior and lower trapezius activity, together with a compensatory increase in muscle activity of the upper trapezius. These three muscles, however, form a crucial part of the force couple responsible for elevating the acromion. Lack of acromial elevation may lead to secondary impingement, especially in a population of overhead athletes, in which the demands on the shoulder joint are extremely high.

Electromyographic activity, isokinetic torque production, and analysis of temporal muscle recruitment are considered relevant variables of muscle function, contributing to functional joint stability. Electromyographic activity of the scapular muscles during arm movement has been extensively investigated. These studies have demonstrated...
decreased activity of the serratus anterior throughout the arm movement in patients with shoulder pathology. Evidence to support the existence of abnormal electromyographic activity in the trapezius muscle in patients with functional shoulder instability or impingement is scarce\(^\text{71,103}\).

Although the majority of investigations regarding scapular muscle function in overhead athletes with shoulder pain consist of analyses of the amount of electromyographic activity, it has been suggested in recent literature that consideration of these traditional parameters of scapular muscle function does not always adequately describe the synchronised activity necessary to control this mobile joint complex\(^\text{67,99,116}\). Other aspects of muscle function such as the temporal sequence of recruitment and the level to which each muscle is activated during movement, are important factors in coordinating scapular motion with humeral movement. Research on recruitment patterns and timing of muscle activity in the shoulder, however, is limited\(^\text{5,15,63,116,118}\). Some studies\(^\text{5,15,63,118}\) examined temporal muscle recruitment in the glenohumeral joint, but literature data on the timing of muscle activity in the scapulothoracic joint are very scarce\(^\text{116}\).

Although EMG studies are considered to provide relevant details regarding muscle activity, they do not directly give information about force output of a muscle group. Isokinetic dynamometry is widely used in the quantitative assessment of muscle performance\(^\text{28}\). In the assessment of shoulder muscle strength, the glenohumeral muscles have been extensively examined\(^\text{17,20,29,31,47,73,75,76,78,89,97,108}\). However, with the exception of some anecdotal data\(^\text{24,127,128}\), research on isokinetic muscle performance of the scapular muscles is limited. Recently, Wilk et al.\(^\text{128}\) emphasised the importance of scapular muscle strength in the overhead athlete. The authors documented the isometric scapular muscle strength values of professional baseball players. To our knowledge, experimental data of isokinetic
scapulothoracic muscle performance in relation to shoulder function do not exist, neither in a healthy population, nor in overhead athletes with shoulder pain.

**Background and aim of this project**

A literature review has shown that an association exists between functional shoulder instability and impingement on the one hand, and scapulothoracic dysfunction including abnormal scapular kinematics and muscle activity, on the other hand. Although numerous studies have examined this association, several important parameters of neuromuscular control in the scapula remain unclear.

**Analysis of trapezius muscle latency (Chapter 2-3)**

*First research question: to what extent is the firing sequence of the trapezius muscle altered in overhead athletes with functional shoulder instability/impingement?*

Biomechanical studies have shown that a smooth scapulothoracic movement pattern is only possible through coordinated muscle activity of the scapular muscles, in which the trapezius and the serratus anterior play a dominant role. Scapulothoracic dysfunction, often established in overhead athletes with shoulder pain, may be a result of dysfunction of these muscles. However, studies examining the firing sequence and the muscle reaction times of trapezius and serratus anterior are nonexistent so far. These investigations, however, would be relevant to our understanding of the aetiology of altered scapulothoracic motion, and may support future directions in rehabilitation of the overhead athlete with shoulder pain. In addition, it has been suggested that shoulder pathology may be caused or aggravated by fatigue in the scapular muscles, resulting in alterations in the scapulohumeral rhythm.
Therefore, an investigation of the effect of muscle fatigue on muscle latency and firing pattern may also be clinically relevant.

Although alterations in timing of scapular muscle activity have often been suggested in the literature, evidence to support these suggestions is scarce. Most of the investigations regarding muscle activity in the trapezius muscle evaluate the amount of muscle activity, and not the timing of onset and recruitment order within the different trapezius parts. However, unconscious muscle reaction is considered to be very relevant to maintaining functional joint stability, especially in a joint which primarily depends on the dynamic stabilisers for optimal function. In addition, a functional subdivision within the trapezius has often been suggested. Examining muscle latency in these muscles may provide relevant information regarding protective reactions and the specific roles of the different muscle portions.

The first purpose of our study is to examine the onset of muscle activity of the three trapezius parts in response to a sudden, unexpected movement of the arm. Since such an investigation has not yet been performed, it is essential to evaluate the reproducibility of the procedure, and to investigate this variable in a healthy non-athletic population.

Only one investigation has been performed regarding the onset of muscle activity in the trapezius and serratus anterior muscle in response to a voluntary movement. Contrary to the glenohumeral joint, onset of muscle activity in response to a sudden perturbation has not yet been studied in the scapulothoracic joint.

In chapter 2, the above mentioned purposes are formulised and investigated. In addition, the effects of fatigue of the scapular muscles on their reaction time are examined. The experimental hypotheses of this study are: (1) our testing protocol, investigating muscle latency of the trapezius muscle in response to a sudden, unexpected movement of the arm, is
reproducible over time, (2) there is a specific sequence in motor activation between the three portions of the trapezius, and (3) fatigue affects the reaction times of the muscles investigated, and their sequence of activation.

In chapter 3, the scapular reaction times are investigated in a population of overhead athletes with impingement symptoms, based on functional instability. The results of the experimental group are compared to those of a healthy athletic control group, and side differences are evaluated. The experimental hypotheses of this study are: (1) there are significant differences in scapular reaction times between the patient and the control group, and (2) there are significant differences in scapular reaction times between the injured and the non-injured side in the patient group.

Analysis of isokinetic muscle performance and associated muscle activity (chapter 4-5)

Second research question: to what extent is an altered muscular protraction-retraction performance present in overhead athletes with functional shoulder instability/impingement?

Measuring muscle performance characteristics has been an integral component of musculoskeletal system assessment for many years. Various assessment approaches involving different types of muscle contractions are available, with isokinetics being the most popular\textsuperscript{23,25,28,57,76}. Although isokinetic contractions have been criticised as a non-functional mode of muscle contraction, they continue to be used extensively because of the objective information on torque, work and power of a muscle group\textsuperscript{25}.

The objective recording of shoulder strength plays an important role for both diagnostic and rehabilitation purposes\textsuperscript{76}. Isokinetic dynamometry is extensively used in the quantitative assessment of glenohumeral shoulder musculature\textsuperscript{17,20,28,29,31,47,73,76,78,89,97,108}. Not only peak
force values, but also agonist-antagonist ratios are considered highly useful measurements to evaluate muscular performance and muscular balance\textsuperscript{31,32,76,128}. However, scapulothoracic muscle performance has not been examined thoroughly. Reliability is specific of a particular movement pattern and needs to be established for any new test method. To our knowledge, no literature exists regarding the isokinetic assessment of scapulothoracic muscle performance.

Therefore, in chapter 4, the day-to-day repeatability of the isokinetic protraction-retraction testing protocol is examined. The experimental hypothesis for this investigation is: the isokinetic protraction-retraction protocol, as presented in the study, is reliable and reproducible over time.

In chapter 5, isokinetic assessment is performed in a group of overhead athletes with shoulder impingement. Bilateral comparisons are performed. Decreased muscle performance is often suggested in the serratus anterior\textsuperscript{95} as well as in the muscles performing the retraction movement\textsuperscript{13}. These assumptions are based on clinical observations\textsuperscript{13,60} or electromyographic data\textsuperscript{77,95}. However, the recorded electromyographic activity is only an indicator of muscular activity level and not directly of the force produced by the muscle\textsuperscript{10,26,39}. Since isokinetic assessment reveals force output rather than individual muscle activity, and the retraction movement is the result of muscle performance of more than one muscle, simultaneous electromyographic analysis is performed during isokinetic assessment of the major scapular muscles, the three trapezius parts and the serratus anterior. This EMG analysis makes it possible to evaluate muscular balance between the different muscles participating in the same movement. The experimental hypotheses for this study are: (1) there are significant differences in force output for the protraction and retraction movement between the injured
and the non-injured side, and (2) there are significant differences in electromyographic activity in the scapular muscles between the injured and the non-injured side.

REFERENCES


Chapter I

CHAPTER 2

SCAPULAR MUSCLE RECRUITMENT PATTERN:
ELECTROMYOGRAPHIC RESPONSE OF THE TRAPEZIUS MUSCLE
TO SUDDEN SHOULDER MOVEMENT BEFORE AND AFTER A
FATIGUING EXERCISE

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Chapter II

ABSTRACT.

STUDY DESIGN: Test-retest reliability study and single – group repeated measures design

OBJECTIVES: To evaluate the Muscle Latency Times of the trapezius muscles to a sudden arm movement in normal shoulders, and to determine if this recruitment pattern is altered as a result of fatigue.

BACKGROUND: Shoulder impingement is often related to altered muscle activity and muscle fatigue in the scapular stabilizers. Fatigue-induced changes in latency times of the trapezius might influence scapular stability.

METHODS AND MEASURES: Muscle Latency Times were investigated in 30 healthy shoulders with Surface-EMG. Muscle activity was measured in all three trapezius-parts and the middle deltoid muscle during a sudden downward falling movement of the arm. Subsequently the shoulder was fatigued on an Isokinetic Dynamometer, after which Muscle Latency Time measurement was repeated.

RESULTS: ANOVA for Repeated Measures revealed significant differences in latency times (p<0.05) among the four muscles of interest. Although there were no significant differences between the three parts of the trapezius muscle (paired T-test with Bonferroni-correction) they all were recruited after the initialization of the deltoid muscle. The recruitment order of the shoulder muscles did not change with muscle fatigue. However, paired t-tests showed that muscle responses were significantly slower in all muscles except the lower trapezius part (p<0.05).

CONCLUSIONS: There is a specific recruitment sequence in the shoulder muscles in response to a sudden arm movement, characterized by initial activation of the middle deltoid muscle, followed by simultaneous contraction of all three parts of the trapezius. This muscle activation pattern is delayed, but not altered with fatigue.

KEY WORDS: neuromuscular properties, scapular latency times, muscular balance, scapular stabilizers.
INTRODUCTION

It is well recognized that the scapula plays an important role in the stability and mobility of the shoulder joint.\textsuperscript{1,33,37,64,65} Especially in sports, where the demands on the shoulder are extremely high, the quality of the movement depends upon the interaction between scapular and glenohumeral kinematics. The maintenance of smooth and coordinated motion requires intact joints and coordinated action among the muscles that move them.\textsuperscript{62}

Many muscles attach to the scapula, some act as scapular rotators; others are concerned with glenohumeral movement. The major upward rotators of the scapula are the upper and lower fibers of trapezius and the lower digitations of serratus anterior\textsuperscript{10,27,31}.

Inman et al.\textsuperscript{27} were the first investigators who emphasized the importance of the muscular force couple as an essential principle in the mechanics of rotation in the scapulothoracic joint. Most authors agree that all parts of the trapezius muscle become more active during both shoulder flexion and abduction\textsuperscript{3,41}, and they agree with Inman\textsuperscript{27} that the trapezius is more active during abduction than during flexion\textsuperscript{3,48}. The midrange of the abduction movement deserves our special attention since the greatest relative amount of scapular rotation occurs in that range\textsuperscript{3,4}.

Although some electromyographic studies showed high muscle activity in all portions of the trapezius muscle in the midrange of abduction\textsuperscript{5,27}, others revealed a plateau of muscle activity during that phase\textsuperscript{3,48}. In the study of Bagg and Forrest\textsuperscript{3} the initial increase in the activity of upper and middle trapezius tended to level off to a fairly constant plateau. This period of reduced increase in activity continued until an angle of between 90 and 120 degrees of abduction had been achieved. The latter authors suggested that this plateau may be caused by the changing function of the muscles, and the significant lengthening of the muscle force arms during that phase of the movement, improving the mechanical advantage of the muscle torque.
Chapter II

Abnormal scapular kinematics and associated muscle function presumably contribute to shoulder pain and pathology. Several studies have revealed scapular muscle dysfunction in patients with shoulder pain.\textsuperscript{17,42,43,46,60} These findings concern patients with anterior instability\textsuperscript{17,46}, multidirectional shoulder laxity\textsuperscript{35}, and subacromial impingement\textsuperscript{60}. Other studies demonstrated the relationship between scapular position or scapulothoracic motion and glenohumeral instability \textsuperscript{28,63,64} or impingement \textsuperscript{42,43}.

The muscular control of the scapula has become a recent focus of therapeutic intervention\textsuperscript{31,33,38,49,50,54}. Most of the literature on this relationship between scapular positioning and shoulder function is based on personal observations rather than research data. Due to the limited scientific results, these training protocols vary widely.

Most authors\textsuperscript{17,30,33,49} agree that weakness in one or more scapular rotators may cause a relative muscular imbalance in the force couples around the scapula, thus leading to abnormal kinematics. However, recently the assumption has been made that not only the intensity of the muscle contraction is determining the scapulothoracic function, but also timing of muscle activity around the scapula is of major importance\textsuperscript{60}.

Several studies, investigating muscle latency times for voluntary and unexpected movements, have been conducted in the knee\textsuperscript{16,58,66,67}, ankle\textsuperscript{6,25,34,44}, and trunk\textsuperscript{13,22,23,68}. Thus, for these joints, temporal muscle recruitment patterns have been examined in a feedback as well as in a feed-forward manner. Research on recruitment patterns and timing of muscle activity in the shoulder however is limited\textsuperscript{2,8,61}. Wadsworth and Bullock-Saxton\textsuperscript{60} examined the temporal recruitment patterns of the scapular rotator muscles during controlled voluntary abduction in the scapular plane. Their results indicated that in non-injured shoulders, the upper trapezius was activated prior to the movement, whereas the lower trapezius was not recruited until after the start of the shoulder movement. To our knowledge, recruitment patterns of the scapular muscles in response
to sudden, unexpected shoulder movements have not been examined. Therefore, the purpose of this study was to evaluate muscle latency times of the deltoid and trapezius in a response to a sudden movement of the arm.

In addition, we wanted to determine the effect of fatigue-inducing exercises on the muscle recruitment pattern of these same muscles.

METHODS

Subjects
Thirty healthy subjects (12 male, 18 female) volunteered to participate in this study. Exclusion criteria were (i) current or past history of shoulder pain, (ii) shoulder instability or chronic cervicobrachial pain symptoms, and (iii) participation in overhead sports. The mean age of the group was 21.04 year (range 18-26 year), the mean body mass was 65.08 kg (range 51-86 kg), and the mean body height was 1.74 m (range 1.63-1.93 m). Twenty-eight subjects were right-handed, two were left-handed. The dominant shoulder was tested in all subjects. All volunteers signed an informed consent. The project has been approved by the Ethical Committee of the Ghent University.

Instrumentation
Prior to electrode application, the skin was prepared with alcohol to reduce skin impedance (typically $\leq 10$ kOhm). Bipolar surface electrodes (Blue Sensor® – Medicotest, Denmark) were placed with a 1 cm inter-electrode distance over the upper, middle and lower portions of the trapezius muscle and the middle section of the deltoid. Electrodes for the upper trapezius were placed midway between the spinous process of the seventh cervical vertebra and the posterior tip
of the acromion process along the line of the trapezius. The middle trapezius electrode was placed midway on a horizontal line between the root of the spine of the scapula and the thoracic spine. The lower trapezius electrode was placed obliquely upward and laterally along a line between the intersection of the spine of the scapula with the vertebral border of the scapula and the seventh thoracic spinous process. The middle deltoid electrode was placed midway between the deltoid tuberosity and the acromion. A reference electrode was placed over the clavicle. Each set of bipolar recording electrodes from each of four muscles was connected to a Noraxon Myosystem 2000 electromyographic receiver (Noraxon USA, Inc., Scottsdale, AZ). The sampling rate was 1000Hz. All raw myo-electric signals were preamplified (overall gain = 1000, common rate rejection ratio 115 dB, Signal to Noise Ratio <1 µV RMS baseline noise, filtered to produce a bandwidth of 10-1000 Hz).

A Biodex system 2 Isokinetic testing device was used as a testing apparatus for the sudden arm movement. The Biodex was put in a non-active mode, so that the subject would not experience any resistance caused by the Isokinetic device during testing. The goniometer of the Biodex was connected to the electromyographic equipment, so that any movement of the lever arm would be detectable on the Noraxon EMG screen.

**Testing procedure**

The first testing session started with a warm up procedure, consisting of shoulder movements in all directions, pushup-exercises against the wall and stretching exercises for the rotator cuff and scapular muscles. We began by recording the resting level of the electrical activity of each muscle. Then verification of EMG signal quality was completed for each muscle by having the subject perform isometric contractions in manual muscle test positions specific to each muscle of interest. Subjects performed three 5-second maximum voluntary isometric muscle
contractions against manual resistance by the principal investigator. A 5-second pause occurred between muscle contractions\textsuperscript{14,19}. As a normalization reference, EMG data were collected during Maximal Voluntary Contraction (MVC) for each muscle. After signal filtering with a low-pass filter (single pass, Butterworth, 6 Hz low pass filter of the 6th order) and visual inspection for artifacts, the baseline activity was subtracted from the MVC signal. Then, the peak average EMG value over a window of 50 ms was selected as a normalization value (100%).

For the testing procedure the subject was seated at the Biodex –system2 Isokinetic device with the arm 90° abducted in the frontal plane. The lever arm was placed horizontal in the resting position, and the shoulder axis for the abduction-adduction movement was aligned with the mechanical axis of the testing device. During testing, subjects were masked and wore headphones to eliminate auditory feedback. The subjects received standardized information about the purpose of the test and were instructed to intercept the sudden perturbation as soon as they felt their arm falling. EMG data were registered during the test, with simultaneous recording of the movement of the lever arm of the Biodex. Three familiarization trials were performed prior to collecting data.

To establish the test-retest reliability of our testing procedure, testing was repeated one week after the initial session. However, after recording EMG activity during sudden arm movement, the shoulder musculature was fatigued on the Isokinetic dynamometer during an abduction–adduction movement. The movement was performed in a concentric-concentric mode at a speed of 120 deg/sec for 34 to 50 repetitions, depending on the subject’s ability. Subjects were instructed to abduct the arm with maximal effort as many times as possible until they were unable to lift their arm above 90°.

Immediately after the fatigue task, the measurement of EMG response to a sudden fall of the arm was repeated, following the same protocol as the first test.
Chapter II

Signal processing and data analysis

a. Muscle Latency Times:

All raw EMG signals were analog/digital (A/D) converted (12-bit resolution) at 1000Hz. Signals then were digitally full-wave rectified and low-pass filtered (single pass, Butterworth, 6 Hz low pass filter of 6th order). Results were normalized to the maximum activity observed during the maximal voluntary trials. After rectifying, filtering and normalization, the electromyographic responses of the muscles to a sudden arm movement were calculated in all three testing sessions (session 1, session 2 pre-fatigue, session 2 post-fatigue) for all four muscles. Muscle latency response was determined by the period of time between the start of the tilting of the goniometer and the beginning of muscle activity. The threshold for muscle activity was set at 10% of the EMG activity of MVC above the resting level\(^{53}\). The resting EMG activity level in the muscles was measured during 500 msec in the period prior to the start of the movement. This baseline activity was considered as the reference base for onset time determination.

Little consensus exists in the literature regarding methods for determination of the onset of EMG activity\(^{14,21}\). It is apparent that any attempt at estimating the precise time at which a muscle begins and ends its activation is fraught with difficulties that cannot be fully addressed with current knowledge and that require further study. Three methods are commonly used to determine the onset time for muscle activation: 1) by visual evaluation of the EMG trace\(^{2,13,58,67}\), 2) methods based on the time taken to reach a predetermined EMG amplitude\(^{34,53,60}\), and 3) calculating the time value at which the EMG signal exceeds the level of 1 or more SD beyond mean of baseline activity\(^{8,16,21,25,44}\). For this investigation, onset time was defined as the time in milliseconds from the starting of the movement, detected by de goniometer, until the muscle contraction. A muscle signal was considered a contraction if it exceeded the trigger level of 10% of the MVC beyond
basic activity. The same basis for muscle activation was used by Rozzi et al\textsuperscript{53}. The 5\% level, often used in onset determination\textsuperscript{9,60} was not appropriate in this investigation since this criterion often interfered with the fluctuation of the basic activity in some of the muscles investigated.

\textit{b. Subject’s Reaction Time:}

The subject’s reaction time was determined by the period between the initiation of the falling movement of the arm and the starting of the upward interception of the subject. The threshold for this interception was set by the start of the upward movement of the goniometer.

\textit{Statistical analysis}

To establish between-day repeatability, Intraclass Correlation Coefficients were calculated for the subject’s reaction time and the muscle latency times obtained in session one and the pre-fatigue condition in session 2. In addition, the results were analyzed with ANOVA for repeated measures to determine mean differences between the two sessions.

Differences in muscle latency times were analyzed with a General Linear Model Two Way ANOVA for Repeated Measure, in which the within factors were fatigue (2 levels) and muscle (4 levels). For this analysis, we used the data, obtained in the pre-fatigue condition and the post-fatigue condition of session 2. Post-hoc comparisons were conducted between the paired muscle groups with paired t-tests. The alpha level for the GLM model was set on 0.05; for each of the multiple pairwise comparisons the Bonferroni correction was used to set alpha on 0.0083.

To compare means between the pre-fatigue and the post-fatigue condition, muscle latency differences were analyzed with a paired t-test for each muscle. A two-tailed test with alpha at 0.05 was conducted. All statistical analysis was performed with the Statistical Package for Social Sciences (SPSS), version 9.0.
RESULTS

a) Reliability study
Test-retest Intraclass Correlations between the first session and the second session/pre-fatigue condition were calculated to be 0.77 for the subject’s latency time to the movement, 0.78 for the muscle latency time of the upper part of the trapezius (UT), 0.73 for the muscle latency time of the middle part of the trapezius (MT), 0.75 for the muscle latency time of the lower trapezius part (LT), and 0.708 for the muscle latency time of the middle part of the deltoid muscle (DM). The results of the Repeated Measures ANOVA revealed no significant differences between the test-retest trials (p = 0.07). The descriptive values for the reproducibility study are summarized in Table 1, session 1 and session 2 pre-fatigue.

b) Muscle Latency Times
The descriptive statistics for the Muscle Latency Times (MLT) are summarized in Table 2. Figure 1 shows a graphic illustration of an electromyographic recording of muscle activity of the upper, middle and lower trapezius and the middle deltoid muscle in response of a sudden arm movement in a single subject in the pre-fatigue condition.
Table 1: Mean, Standard Deviations (SD) and Standard Error of Measurement (SEM) for the subject’s reaction time (SRT) and muscle latency times (MLT) for the upper trapezius (UT), middle trapezius (MT), lower trapezius (LT), and middle deltoid (DM), in the first session and the pre-fatigue condition of the second session (N=30). The corresponding Intraclass Correlation Coefficient (ICC) values are also presented.

<table>
<thead>
<tr>
<th></th>
<th>Session 1</th>
<th>Session 2 pre-fatigue</th>
<th>ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MEAN (msec)</td>
<td>SD</td>
<td>SEM</td>
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<tr>
<td>UT-MLT</td>
<td>164.68</td>
<td>64.50</td>
<td>12.9</td>
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<tr>
<td>MT-MLT</td>
<td>179.92</td>
<td>94.44</td>
<td>18.8</td>
</tr>
<tr>
<td>LT-MLT</td>
<td>193.40</td>
<td>93.68</td>
<td>18.7</td>
</tr>
<tr>
<td>DM-MLT</td>
<td>143.44*</td>
<td>58.65</td>
<td>10.7</td>
</tr>
<tr>
<td>SRT</td>
<td>295.80</td>
<td>72.34</td>
<td>14.4</td>
</tr>
</tbody>
</table>

*: significantly different from UT-MLT (p<0.0083), MT-MLT (p<0.0083), and LT-MLT (p<0.0017) for the same session

Figure 1: raw EMG data of the upper trapezius (UT), middle trapezius (MT), lower trapezius (LT) and middle deltoid (DM), in response to a sudden downward arm movement, monitored by an electrogoniometer (gonio) (Noraxon Myosystem 2000®, Myoresearch 97 software program®)
The two-way ANOVA for repeated measures (General Linear Model) revealed significant differences among the muscles in the pre-fatigue and in the post-fatigue condition ($p < 0.05$) and between the values in the pre- and post-fatigue condition ($p < 0.05$). Post-hoc paired t-tests with Bonferroni correction showed that the muscle latency time of the middle part of the deltoid was significantly shorter than the muscle latency times of each of the trapezius muscles, but there were no significant latency differences among the three parts of the trapezius muscle (Table 2, pre-fatigue).

Table 2: Mean, Standard Deviations (SD) and Standard Error of Measurement (SEM) for the subject’s reaction time (SRT) and muscle latency times (MLT) for the upper trapezius (UT), middle trapezius (MT), lower trapezius (LT), and middle deltoid (DM), in the pre-fatigue condition and the post-fatigue condition of the second session ($N=30$). Mean increase in muscle latency response is also presented (in % to pre-fatigue condition).

<table>
<thead>
<tr>
<th></th>
<th>Session 2 pre-fatigue</th>
<th>Session 2 post-fatigue</th>
<th>% delay (mean difference) pre-post-fatigue (p-value)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MEAN (msec)</td>
<td>SD</td>
<td>MEAN (msec)</td>
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<tr>
<td>UT-MLT</td>
<td>159.63</td>
<td>56.47</td>
<td>189.10</td>
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<td>MT-MLT</td>
<td>161.13</td>
<td>60.00</td>
<td>191.87</td>
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<tr>
<td>LT-MLT</td>
<td>167.48</td>
<td>65.66</td>
<td>199.33</td>
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<tr>
<td>DM-MLT</td>
<td>141.43</td>
<td>65.84</td>
<td>178.45</td>
</tr>
<tr>
<td>SRT</td>
<td>285.20</td>
<td>64.29</td>
<td>343.13</td>
</tr>
</tbody>
</table>

*: significantly different from UT-MLT ($p < 0.0083$), MT-MLT ($p < 0.0083$), and LT-MLT ($p < 0.0017$) for the same session

**: significantly different from UT-MLT ($p < 0.0083$), MT-MLT ($p < 0.0083$), and LT-MLT ($p < 0.0083$) for the same session
c) *Effects of fatigue on the muscle latency times:*

The average number of repetitions during the fatigue test was 43 (SD=3.8). The average fatigue-index, defined as the percentage decrease in work from the first third to the last third of the fatigue task, was 45% (SD=10.6). Descriptive analysis of latency values after the fatigue protocol is presented in Table 2 (session 2 - post-fatigue).

Paired t-tests between the pre-fatigue and post-fatigue conditions for each muscle group revealed significant increased muscle latency times for all muscles except the lower trapezius (p<0.05). Delay in muscle onset averaged 18.5% in the upper trapezius, 19.1% in the middle and lower trapezius, and 26.2% in the middle deltoid muscle.

The differences in Muscle Latency Times between the four muscles were post-hoc analyzed with paired t-tests with Bonferroni correction. A similar recruitment pattern as in the pre-fatigue situation was demonstrated: The muscle latency time of the middle deltoid muscle was significantly shorter than the latency times of each of the trapezius parts, but there were no significant latency differences among the three parts of the trapezius muscle (Table 1, session 2 post-fatigue).

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d) *Effects of fatigue on Subject’s Reaction Time.*

The descriptive statistics for the Subject’s Reaction Times (SRT) are summarized in Table 1. The results revealed an increase in the Subject’s Reaction Time to the initiation of the movement (p<0.01) after fatigue.
DISCUSSION

In our study ICC for the muscle latency times and the subject reaction time ranged from 0.71 to 0.78. Taking into account the nature of the task, day-to-day reliability of the testing procedure was considered acceptable. Therefore, in our judgment, our testing procedure may be considered a reliable method of determining the sequence of muscle recruitment. Although the latency times of all the muscles decreased in the second session, the rank at which the muscles became active remained unchanged.

The results of our investigation revealed a pattern of recruitment of the shoulder muscles in which the deltoid muscle fires significantly prior to the trapezius muscle in response to a sudden abduction movement of the shoulder passively held at 90° abduction. A specific sequence was detected between the different trapezius parts, but no statistical difference could be demonstrated. This trapezius muscle contraction seems to be reactive after the start of the activity of the deltoid, and not, as we would have expected, in a feed-forward stabilizing activity, prior to the activation of the prime mover (the deltoid). Indeed, as the movement was unexpected, and the subject received no external clues regarding the start of the movement, anticipating muscle contraction of the stabilizers, prior to initiation of prime mover activity, was impossible. The question arises if the stimulus for trapezius muscle activity is the initiation of muscle activity in the deltoid muscle, or rather the start of the movement of the arm (in which case all four muscles react in response to the beginning of the movement, but the deltoid reacts faster). The differences between the latency time of the deltoid muscle and the latency time of the upper trapezius are 18.2 msec for the pre-fatigue session, and 10.7 msec for the post fatigue session. Previous studies on trunk muscles defined “feed-forward” muscle contraction as muscle activity prior to or shortly after the onset of
activity of the prime mover of the limb. Following that definition, any trapezius muscle activity occurring less than 50 ms after the onset of deltoid EMG activity cannot be mediated by feedback from the deltoid muscle activity, and can be considered to be feedforward.\textsuperscript{23} In our study, differences between muscle latency times are less than 50 msec. Thus, trapezius muscle activity may be considered as reactive in response to the movement of the arm, but not as a feedback reaction to the muscle activity of the deltoid muscle. However, since signal processing and onset determination methods differ from the methods used in this investigation, one should be careful discussing comparisons between timing parameters disclosed in different studies.

The trapezius muscle seems to react as a unit stabilizing the scapula in response to a sudden arm movement in normal shoulders. However, our results suggest a recruitment sequence within the trapezius muscle with a delay in activation of the lower trapezius, although not statistically significant. The lack of significance may be due to the large standard deviations of the muscle latency times of the lower trapezius, which may obscure an existing recruitment order.

Anatomic and histochemical studies regarding trapezius muscle composition found some functional subdivisions within the trapezius muscle. Lindman et al.\textsuperscript{39,40} found that the ascending portion of the trapezius muscle (arising from the spinous processes and interspinous ligaments of approximately the T₄ through T₁₂ vertebrae, and attaching in the region of the tubercle at the medial end of the spine of the scapula\textsuperscript{56}) had a predominance of type I fibers, whereas the most superior parts of pars descendens (from the medial third of the superior nuchal line and the ligamentum nuchae to the posterior border of the lateral third of the clavicle\textsuperscript{56}) had a higher frequency of type II fibers. These differences in fiber type might reflect different functional demands on the trapezius muscle parts in various head, neck, and shoulder movements. The author concluded that the lower trapezius seems best suited for postural and stabilizing functions in the shoulder and arm movements, whereas the upper trapezius seems best suited for phasic
activities. Similar conclusions can be drawn from a dissection study revealing the fascicular anatomy of the trapezius\textsuperscript{30}. Based on the orientation of the fibers of the lower trapezius, it was suggested that the role of the lower part of the trapezius is more consistent with maintaining horizontal and vertical equilibrium of the scapula rather than generating net torque\textsuperscript{30}. In addition, Johnson et al. hypothesized that the thoracic fibers of the trapezius muscle do not appreciably change length throughout the entire range of upward rotation of the scapula\textsuperscript{30}. Hence the contribution of the lower trapezius to net torque about the axis of rotation of the scapula was suggested to be limited. In this investigation, visual inspection of the processed EMG signal often showed a different activation pattern in the lower trapezius as to the upper trapezius (figure 1), characterized by a rather low signal, and a rather slow but consistent increase. However, we should be very cautious interpreting these anecdotal data since they were not confirmed by the statistical analysis. Future research should thoroughly examine the recruitment order and intensity of muscle activity in both muscle groups.

In this investigation, mean muscle latency times for all muscles involved were between 141 msec and 167 msec in the pre-fatigue test. Response times for voluntary movement have been reported to have a minimum delay of 170 milliseconds\textsuperscript{15}, although some authors reported shorter voluntary responses of 117.7 msec in the quadriceps and 157.1 msec in the gastrocnemius\textsuperscript{12}. Wojtys\textsuperscript{66} referred to voluntary muscle activity latency in the range of 220 to 360 msec. Substantially longer delays (as much as 400 msec) have been reported in the literature as well\textsuperscript{26}. We could not find experimental data describing the muscle latency times of the trapezius muscle and deltoid muscle in response to a sudden arm movement. However, we should be very cautious interpreting the absolute muscle latency times, found in this investigation. In order to sufficiently level off the fluctuations in the basic activity and adequately determine the onset of muscle activity in response to the movement of the arm, a single pass filter (Butterworth) was used. This
filter results in a time shift of the amplitude level of the EMG signal. Since the purpose of this study was to evaluate the relative timing of trapezius muscle activity in regard to deltoid activity, and all muscles were analyzed in the same manner, we should focus on the differences between the muscles involved, rather than interpreting the absolute values of the muscle latency times.

In contrast to muscle latency investigation in response to a sudden, unexpected movement, the recruitment order of the scapular muscles and the deltoid muscle during voluntary movements have been investigated. Wadsworth and Bullock-Saxton measured muscle activity during voluntary movements in the scapular rotators in injured and non-injured swimmers. The muscle activation data for the control group revealed that the average temporal recruitment pattern of the scapular rotators consisted of initial activity of the upper trapezius prior to arm abduction, followed by serratus anterior activation, after abduction began. Lower trapezius was not activated until the shoulder was abducted to 15°. The results of his study indicated a significant increased variability in the timing of activation in the upper and lower part of the trapezius muscle in the injured shoulders, reflecting inconsistent or poorly coordinated muscle activation. Although not statistically significant, muscle latency in our study showed the same tendency of temporal sequence as shown by Wadsworth and Bullock-Saxton for their control group with regard to the ranking of upper and lower trapezius muscle.

Our sample group consisted of healthy subjects, and participation in overhead sports was an exclusion criterion. Healthy shoulders were selected because the aim of our study was to define a normal muscle recruitment sequence in the trapezius muscle. However, we must take into account that the use of healthy subjects is a limitation to our study, and further research should emphasize muscle recruitment patterns in patients with abnormal scapular kinematics.

The exclusion of participation in overhead sports is based on the assumption that athletes presumably show some adaptive changes in muscle latency times due to repetitive overhead.
movements. Augé and Morrison examined the infraspinatus spinal stretch reflex in normal, athletic and multidirectionally unstable shoulders. The results from this investigation showed that athletic shoulders exhibited a more quiescent spinal stretch response than normal shoulders. These results were in agreement with previous observations that reflex characteristics vary between subjects with variations in muscle activity levels or coordination patterns.

In this study, the age of the subjects ranged from 18 to 26 years. This narrow age range was chosen to exclude the age-factor as an affecting element in our investigation. In a normal population, proprioceptive acuity declines with chronological age. This possibly may lead to impaired general motor control and coordination.

In our investigation, muscle responses showed considerable slowing after they were fatigued with an isokinetic abduction-adduction movement task. These findings suggest that muscular fatigue affects the onset of muscle activity in the trapezius and deltoid muscle. The relationship found between muscle fatigue and neuromuscular qualities has been demonstrated in the knee and the ankle. In the shoulder, most of the studies investigating altered proprioception in relation to muscle fatigue, demonstrate reduced acuity of position or movement sense in the presence of muscle fatigue. To our knowledge, no literature exists demonstrating altered timing of muscle activation in the scapular muscles after a fatigue-inducing task.

We found delays in muscle latency times after fatigue for all muscle groups (all significant but the lower trapezius). Delay averaged 18.5% in the upper trapezius, 19.1% in the middle trapezius, and 26.2% in the middle deltoid muscle. These results were consistent with the findings reported by Wojtys et al. These authors found average increase in muscle latency times of the gastrocnemius, hamstrings and quadriceps muscle between 17.5% and 28.5% after a fatigue protocol for the knee. A possible mechanism explaining the delay in muscle onset time might be a decrease in motoneuron firing rates during muscle fatigue. These findings were reported by
Bigland-Ritchie et al. The reason for this outcome was thought to be that as motoneuron firing rates decrease, muscle latency times should lengthen. A decrease in conduction velocity, which has previously been shown to occur during fatiguing isometric-type contractions may also be the underlying mechanism for this increase in muscle latency times.

Delayed muscle onset time due to fatigue might have considerable clinical implications. In the assumption that muscles are fatigued during sports movements, this possibly could lead to altered scapular kinematics. Thus the repetitive nature of both daily and sports activities may subject the upper extremity to overuse injuries related to fatigue in the scapular muscles.

We initially hypothesized that an exercise protocol inducing muscular fatigue would not only delay the onset of muscle activity, but also alter the sequence of activation in the trapezius muscle parts. However, our results demonstrated that the recruitment order of the trapezius muscle and the deltoid muscle in healthy shoulders did not change with muscle fatigue. Therefore we can conclude that in normal shoulders the recruitment sequence is not altered after fatigue. These findings are in agreement with Wojtys et al. who reported that hamstrings and quadriceps muscle fatigue did not change the order of muscle recruitment in response to a tibial translation stimulus; however, muscle latency times were slowed after fatigue.

Apparently, in our investigation, fatigue affects the global subject’s latency time and the individual muscle latency times, but not the intermuscular timing of muscle contraction. Noticeable was the observation that, contrary to the other muscles, the delay in latency time of the lower trapezius after fatigue exposed a lack of significance (p = 0.09). However, the muscle latency times of the lower trapezius muscle showed considerable variability, particularly in the post-fatigue condition (Mean = 199, SD = 109 msec). Since statistical experts encourage researchers to analyze and discuss power when they report p values between 0.05 and 0.15, post hoc Power Estimation was performed on the statistical test for this particular muscle, and
showed to be low (0.47). This might possibly explain the lack of significant differences in the results for this muscle after the fatigue-inducing task.

CONCLUSIONS

Some implications can be drawn from the results of this study. Our investigation shows that in normal shoulders, the trapezius muscle seems to act like a unit in a response to a sudden arm movement, after the onset of the prime mover of the shoulder, the middle deltoid muscle. There is some tendency to a slower onset time for the lower trapezius part as compared to the upper and middle trapezius, but this was not statistically significant.

The muscle onset times in all muscles but the lower trapezius part were delayed after fatigue, suggesting that muscle recruitment of the upper and middle trapezius may be influenced by fatigue. Further research studies of recruitment patterns in other circumstances are needed. Future investigations should also emphasize muscle recruitment patterns in patients with abnormal scapular kinematics.
REFERENCES


CHAPTER 3

SCAPULAR MUSCLE RECRUITMENT PATTERN: TRAPEZIUS MUSCLE LATENCY IN OVERHEAD ATHLETES WITH AND WITHOUT IMPINGEMENT SYMPTOMS

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ABSTRACT

Altered muscle activity in the scapular muscles is commonly believed to be a contributing factor to shoulder impingement syndrome. However, one important measure of the muscular coordination in the scapular muscles, the timing of temporal recruitment pattern, is undetermined. The purpose of this study was to evaluate the timing of trapezius muscle activity in response to an unexpected arm movement in overhead athletes with impingement symptoms, in comparison to normal shoulders. Thirty non-impaired overhead athletes and 39 overhead athletes with impingement participated in the study. Muscle-Latency-Times were measured in all three trapezius parts and the middle deltoid part during a sudden downward falling movement of the arm. Relative-Muscle-Latency-Times (RMLT) of trapezius muscle in respect to muscle onset of the deltoid muscle were calculated. Analysis of Variance revealed significant differences in the RMLT between the impingement and the control group. Compared to the non-impaired subjects, those with impingement show a delay in muscle activation of the middle and lower trapezius muscle. The results of this study indicate that overhead athletes with impingement symptoms show abnormal timely muscle recruitment in the trapezius muscle.
INTRODUCTION

Chronic shoulder pain is probably the most common upper extremity problem in recreational and competitive overhead athletes\(^1, 34, 43\). Throwing athletes, athletes involved in racquet sports, volleyball players and swimmers need full, unrestricted upper extremity function to optimally perform in their sport\(^36\).

Non-traumatic shoulder pain in the overhead athlete is a diagnostic challenge. The causes of chronic shoulder pain are numerous, but often difficult to identify and diagnose\(^6, 9, 37, 58\). Research indicates that shoulder impingement is the most common cause of shoulder pain in overhead athletes\(^2, 53\). The term shoulder impingement was first introduced by Neer\(^41\) in 1972 and represents mechanical compression of the rotator cuff and subacromial bursa against the anterior undersurface of the acromion and coracoacromial ligament, especially during elevation of the arm. Primary impingement can be defined as impingement caused by outlet stenosis in the subacromial space in a stable shoulder\(^51\). According to various authors, symptoms of impingement in the throwing athlete are often related to glenohumeral instability\(^22, 23, 35\). This secondary form of impingement can be defined as impingement secondary to instability of the shoulder\(^51\). Different anatomical structures can be impinged internally or externally, probably depending on the motion and loading put on the shoulder during the pain-provoking activity\(^51\). However, a possible instability in the shoulder is often “silent” and difficult to demonstrate by ordinary tests and has therefore by some been termed “functional instability”. It is now thought that functional instability in the shoulder may lead to a vicious circle involving microtrauma and secondary impingement, and may eventually lead to chronic shoulder pain\(^51\).

It is commonly accepted that the scapula plays an important role in normal shoulder function\(^3, 28, 40\). Especially in sports, where demands on the shoulder are extremely high, the quality of
movement depends upon the interaction between scapular and glenohumeral kinematics\(^9\). Functional stability of the scapula requires optimal positioning, smooth muscular balance in the force couple around the scapula, and correct timing of muscle activity of the scapular rotators. Temporal sequence of recruitment and the level to which each muscle is activated during movement are important factors in coordinating scapula motion with humeral elevation\(^28\).

Because the scapula plays a critical role in controlling the position of the glenoid, relatively small changes in the action of scapulothoracic muscles can affect the alignment and forces involved in movement around the glenohumeral joint\(^47\). This may lead to tensile overload of the rotator cuff and impingement symptoms\(^8, 36, 38\). Clinical experience\(^26, 40, 58\) as well as scientific data\(^14, 31, 33, 46, 55\) show that athletes with shoulder pathology consistently demonstrate abnormalities in scapular rotator activity. Intensity of muscle activity in the scapular muscles have been investigated by a number of researchers in healthy shoulders\(^5, 30, 39\), and in shoulders with glenohumeral instability\(^14, 33\) or impingement\(^31, 46\). Most authors suggest, based on their data, alterations in muscle activity in upper trapezius, lower trapezius and serratus anterior in patients with symptoms of impingement\(^31, 46, 55\).

Temporal scapular recruitment patterns in relation to voluntary movement have been investigated in swimmers with subacromial impingement\(^55\). Wadsworth et al.\(^55\) found increased variability in the timing of activation of trapezius and serratus anterior in the injured shoulder, and delayed muscle activity in the serratus anterior in the non-injured extremity. The findings of this study suggest that injury reduces the consistency of muscle recruitment in relation to controlled voluntary movement. However, to our knowledge, no research exists regarding the timing of muscle activity of the scapular rotators in response to a sudden, unexpected movement in overhead athletes with impingement symptoms.
The aim of this study was to investigate the temporal recruitment pattern of the trapezius muscle in relation to glenohumeral movement in overhead athletes showing symptoms of impingement. Therefore a comparative study investigating timing of muscle activity in the upper, middle and lower trapezius was conducted, evaluating the differences in muscle latency times between overhead athletes with current shoulder pain and impingement symptoms, and non-symptomatic overhead athletes.

MATERIALS AND METHODS

Subjects

Both shoulders from a total of 69 subjects were tested. The patient group consisted of 39 overhead athletes from various overhead sports (26 males, 13 females) with unilateral shoulder pain on the dominant side. The average age was 25.9 years (range: 16-35). Twenty patients were volleyball players, 10 tennis players, 4 swimmers, and 5 athletes from other overhead sports. Thirty healthy overhead athletes with no history of shoulder injuries (19 males, 11 females) served as control group. The average age was 22.5 years (range: 18-36). The subjects participated in volleyball (15), tennis (8), swimming (3), and other overhead sports (4).

All subjects completed questionnaires about their history of shoulder pain, their training and athletic performance history. Their functional ability was assessed by the modified Rowe-score\textsuperscript{59}. The Rowe score can range from 0 to 100, with lower scores indicating worse function. The Rowe scores, and the demographic characteristics of both groups of subjects are presented in Table 1.
Table 1: Anthropometric and Demographic data of the non-injured and impingement groups

<table>
<thead>
<tr>
<th>Variable</th>
<th>Non-injured subjects (N = 30)</th>
<th>Subjects with shoulder impingement (N = 39)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Age (years)</td>
<td>22.5</td>
<td>4.3</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.78</td>
<td>0.09</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>68.6</td>
<td>9.3</td>
</tr>
<tr>
<td>Duration shoulder pain (months)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>ROWE-score</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

NA = not applicable

A shoulder with symptoms of shoulder impingement was determined by history and confirmed by physical examination to check for signs of impingement (Neer, Hawkins, supraspinatustest, apprehension and relocation test). The subjects were referred by medical consultants, and were examined by the same orthopedic surgeon (third author).

Patients were included in the impingement group if they had at least 2 of the following 5 criteria:

1. Positive Neer sign: reproduction of pain when the examiner passively flexes the humerus to end-range with overpressure.
2. Positive Hawkins’ sign: reproduction of pain when the shoulder is passively placed in 90° forward flexion and internally rotated to end-range.
3. Positive Jobe’s sign: reproduction of pain and lack of force production with isometric elevation in the scapular plane in internal rotation (empty can)
4. Pain with apprehension: reproduction of pain when an anteriorly directed force is applied to the proximal humerus in the position of 90° of abduction and 90° of external rotation
5. Positive relocation: reduction of pain after a positive apprehension test when a posteriorly directed force is applied to the proximal humerus in the position of 90°/90°.
Trapezius Latency in overhead athletes

For inclusion, at least one impingement sign needed to be positive, with in addition a second positive impingement test or a painful apprehension / positive relocation test. It is thought that patients with minor instability and secondary impingement will experience pain, but not apprehension with these tests\textsuperscript{9,51}.

Subjects were excluded if they had a history of dislocation of the shoulder, shoulder surgery, current symptoms related to the cervical spine, or documented structural injuries to the shoulder complex. All subjects gave their written informed consent to participate in this study. The study was approved by the Ethical Committee of the Ghent University.

Instrumentation

Prior to electrode application, the skin was prepared with alcohol to reduce skin impedance (typically < 10 kOhm). Bipolar surface electrodes (Blue Sensor\textsuperscript{®} – Medicotest, Denmark) were placed with a 1 cm inter-electrode distance over the upper, middle and lower portions of the trapezius muscle and the middle section of the deltoid\textsuperscript{7}. Electrodes for the upper trapezius were placed midway between the spinous process of the seventh cervical vertebra and the posterior tip of the acromion process along the line of the trapezius. The middle trapezius electrode was placed midway on a horizontal line between the root of the spine of the scapula and the third thoracic spinous process. The lower trapezius electrode was placed obliquely upward and laterally along a line between the intersection of the spine of the scapula with the vertebral border of the scapula and the seventh thoracic spinous process. The middle deltoid electrode was placed midway between the deltoid tuberosity and the acromion. A reference electrode was placed over the clavicle. Each set of bipolar recording electrodes from each of four muscles was connected to a Noraxon Myosystem 2000 electromyographic receiver.
Chapter III

(Noraxon USA, Inc., Scottsdale, AZ). The sampling rate was 1000Hz. All raw myo-electric signals were preamplified (overall gain = 1000, common rate rejection ratio 115 dB, Signal to Noise Ratio <1 µV RMS baseline noise, filtered to produce a bandwidth of 10-1000 Hz).

A Biodex® system 2 isokinetic testing device (Biodex Medical Systems, Inc., 20 Ramsay Road, box 702, Shirley, New York, U.S.A.) was used as a testing apparatus for the sudden arm movement. The Biodex® was put in a non-active mode, so that the subject would not experience any resistance caused by the isokinetic device during testing. The goniometer of the Biodex® was connected to the electromyographic equipment, so that any movement of the lever arm would be detectable on the Noraxon EMG screen.

Testing procedure

We began by recording the resting level of the electrical activity of each muscle. Then verification of EMG signal quality was completed for each muscle by having the subject perform maximal isometric contractions in manual muscle test positions specific to each muscle of interest\textsuperscript{17,27,44}. For the upper trapezius muscle, resistance was applied to abduction of the arm, since Schludt & Harms-Ringdahl\textsuperscript{49} found this position superior to shoulder girdle elevation in activating the upper trapezius muscle. The middle trapezius muscle was tested by applying resistance to horizontal abduction in external glenohumeral rotation\textsuperscript{27}. For lower trapezius testing, the arm was placed diagonally overhead in line with the lower fibers of the trapezius. Resistance was applied against further elevation\textsuperscript{27}. Middle deltoid manual muscle testing was performed by resisting abduction in the frontal plane in a starting position of 70° of abduction\textsuperscript{27}. Subjects performed three 5-second maximum voluntary isometric muscle contractions against manual resistance by the principal investigator. A 5-second pause
occurred between muscle contractions\textsuperscript{11, 16}. As a normalization reference, EMG data were collected during Maximal Voluntary Contraction (MVC) for each muscle. After signal filtering with a low-pass filter (single pass, Butterworth, 6 Hz low pass filter of the 6th order) and visual inspection for artifacts, the baseline activity was subtracted from the MVC signal. Then, the peak average EMG value over a window of 50 ms was selected as a normalization value (100\%).

For the testing procedure the subject was seated at the Biodex\textsuperscript{®}–system2 isokinetic device with the arm 90° abducted in the frontal plane (figure 1). The lever arm was placed horizontal in the resting position, and the shoulder axis for the abduction-adduction movement was aligned with the mechanical axis of the testing device. The upper limb of the subject was resting on the lever arm, fixed by the Biodex\textsuperscript{®} straps. During testing, subjects were masked and wore headphones to eliminate auditory feedback. The subjects received standardized information about the purpose of the test and were instructed to intercept the sudden perturbation as soon as they felt their arm falling. For the test, the investigator released the lever arm from the locked position with the hold/resume button. EMG data were registered during the test, with simultaneous recording of the movement of the lever arm of the Biodex\textsuperscript{®}. In the patient group, the non-injured arm was tested first, followed by the painful arm. In the control group, the non-dominant arm was tested before the dominant arm. Three familiarization trials for both arms were performed prior to data collection.
Signal processing and data analysis

All raw EMG signals were analog/digital (A/D) converted (12-bit resolution) at 1000Hz. Signals then were digitally full-wave rectified and low-pass filtered (single pass, Butterworth, 6 Hz low pass filter of 6th order). Results were normalized to the maximum activity observed during the maximal voluntary trials. After rectifying, filtering and normalization, the electromyographic responses of the muscles to a sudden arm movement were calculated for all four muscles. Muscle latency response was determined by the period of time between the start of the tilting of the goniometer and the beginning of muscle activity. The threshold for muscle activity was set at 10% of the EMG activity of MVC above the resting level\textsuperscript{10, 45}. A muscle signal was considered a contraction if it exceeded the trigger level of 10% of the MVC beyond basic activity.

The resting EMG activity level in the muscles was measured during 500 msec in the period prior to the start of the movement. This baseline activity was considered as the reference base for onset time determination.
The reproducibility of our experimental procedure, EMG data analysis and onset determination were discussed in a previous paper\textsuperscript{10}. Test-retest Intraclass Correlations were calculated to be 0.78 for the muscle latency time of the upper part of the trapezius (UT), 0.73 for the muscle latency time of the middle part of the trapezius (MT), 0.75 for the muscle latency time of the lower trapezius part (LT), and 0.71 for the muscle latency time of the middle part of the deltoid muscle (DM).

**Statistical analysis**

Means, standard deviations, and ranges were calculated for all dependent variables, namely the Muscle Latency Times (MLT) of the four muscles of interest (upper, middle and lower trapezius, middle deltoid) on both sides (non-dominant / uninjured and dominant / injured side) for both groups (impingement group and overhead athletes without shoulder pain). In addition, Relative Muscle Latency Times (RMLT) were calculated for the three trapezius parts in relation to muscle onset of the deltoid muscle.

Since all data were normally distributed with equal variances, parametric tests were used for statistical analysis. Differences in muscle latency times were analyzed with a General Linear Model Two Way ANOVA, in which the within subject factors were side (2 levels) and muscle (4 levels). The between subject factor was group (2 levels). Post-hoc analyses were performed using a Bonferroni procedure when a significant difference was found with ANOVA. Comparisons of Relative Muscle Latency Times between the non-dominant / non-injured side and the dominant / injured side within the 2 groups were made using paired $t$-tests, with alpha set on 0.05. To compare Relative Muscle Latency Times between groups,
independent t-tests were used. The alpha level was set on 0.05. All statistical analysis was performed with the Statistical Package for Social Sciences (SPSS), version 10.0.

Power analysis of our investigation revealed a Power of 82%. Calculations regarding effect size were based on the smallest significant difference found in our previous study on healthy shoulders\textsuperscript{10}.

**RESULTS**

The descriptive statistics for the Muscle Latency Times and the Relative Muscle Latency Times for both sides and both groups are summarized in tables 2 and 3. For purposes of this study, Relative Muscle Latency Time of a muscle is defined as the muscle latency time of the muscle of interest minus the muscle latency time of the middle deltoid muscle.

The General Linear Model Two-Way ANOVA revealed significant differences among the muscles ($p < 0.01$), between the two groups ($p < 0.01$), and between both sides ($p < 0.05$). There was no significant group x side interaction effect ($p = 0.71$). However, the results revealed a significant group x muscle interaction effect ($p < 0.01$).

Post hoc comparisons between groups showed significant longer muscle latency times in the patient group for the middle trapezius and lower trapezius on the injured side compared to the dominant side of the control group, and the same significant differences for both muscle groups on the non-injured side compared to the non-dominant side of the control group (table 2).

Since the temporal recruitment order was of particular interest, differences between groups and within each group between both sides were analyzed for the Relative Muscle Latency Times (RMLT) (table 3). On both sides, the Relative Muscle Latency Times of the middle
and lower trapezius were significantly longer in the patient group, compared to the control group. In the comparison between both sides, the RMLT of the lower trapezius in the patient group was significantly longer on the injured side compared to the non-injured side, and the RMLT of the middle trapezius in the control group was significantly shorter on the dominant, compared to the non-dominant side.

The results of the Post-hoc analysis for the factor muscle are summarized in table 4. Post-hoc analysis between the muscles showed for the patient group on the non-injured side that the muscle latency time of the middle part of the deltoid muscle was significantly shorter than those of each of the trapezius muscles. Among the trapezius parts, only a significant difference was found between the upper and lower trapezius. On the injured side of the patient group, multiple pairwise comparisons between muscles showed significant differences among all the muscles involved: the muscle latency times of the trapezius muscles were significantly longer than muscle onset of the middle deltoid, and within the trapezius, the recruitment order was upper trapezius – middle trapezius – lower trapezius, with significant differences between all three muscle parts.

The results of the post hoc tests for the factor muscle on the non-dominant side of the control group revealed significant differences between the middle part of the deltoid muscle on one hand, and the three trapezius parts on the other hand, but no significant differences among the trapezius parts. On the dominant side of the control group, a significant difference was found between the middle part of the deltoid muscle and upper and lower trapezius. No significant differences were found between onset times of middle deltoid and middle trapezius muscle. Within the trapezius, the results revealed significant differences between muscle onset of middle and lower trapezius.
Table 2: Mean and Standard Deviations (SD) for the Muscle Latency Times (MLT) of upper trapezius (UT), middle trapezius (MT), lower trapezius (LT), and middle deltoid (DM) at the non-injured (non-dominant) and injured (dominant) side for the patient group (N = 39), and at the non-dominant and dominant side for the control group (N = 30).

<table>
<thead>
<tr>
<th></th>
<th>Patient group (N = 39)</th>
<th>Control group (N = 30)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non-injured side</td>
<td>Injured side</td>
</tr>
<tr>
<td>MLT – UT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (msec)</td>
<td>167.8</td>
<td>149.9</td>
</tr>
<tr>
<td>SD</td>
<td>30.9</td>
<td>36.5</td>
</tr>
<tr>
<td>MLT – MT</td>
<td>172.3°</td>
<td>158.4°</td>
</tr>
<tr>
<td>Mean (msec)</td>
<td>32.6</td>
<td>34.1</td>
</tr>
<tr>
<td>MLT – LT</td>
<td>177.3°</td>
<td>174.3°</td>
</tr>
<tr>
<td>Mean (msec)</td>
<td>33.8</td>
<td>38.9</td>
</tr>
<tr>
<td>MLT – DM</td>
<td>149.3</td>
<td>137.1°</td>
</tr>
<tr>
<td>Mean (msec)</td>
<td>30.5</td>
<td>31.2</td>
</tr>
</tbody>
</table>

*: significant group differences (p < 0.01)
°: significant group differences (p < 0.05)

Table 3: Mean and Standard Deviations (SD) for the Relative Muscle Latency Times (RMLT) of upper trapezius (UT), middle trapezius (MT), and lower trapezius (LT) (relative to muscle onset of the deltoid muscle) at the non-injured (non-dominant) and injured (dominant) side for the patient group (N = 39), and at the non-dominant and dominant side for the control group (N = 30).

<table>
<thead>
<tr>
<th></th>
<th>Patient group (N=39)</th>
<th>Control group (N=30)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non-injured side</td>
<td>Injured side</td>
</tr>
<tr>
<td>RMLT-UT</td>
<td>18.5</td>
<td>12.8</td>
</tr>
<tr>
<td>Mean (msec)</td>
<td>16.5</td>
<td>14.2</td>
</tr>
<tr>
<td>Range</td>
<td>-14/56</td>
<td>-16/66</td>
</tr>
<tr>
<td>RMLT-MT</td>
<td>22.9°</td>
<td>21.3°</td>
</tr>
<tr>
<td>Mean (msec)</td>
<td>13.6</td>
<td>14.5</td>
</tr>
<tr>
<td>Range</td>
<td>-8/50</td>
<td>-11/75</td>
</tr>
<tr>
<td>RMLT-LT</td>
<td>28.0°</td>
<td>37.2°</td>
</tr>
<tr>
<td>Mean (msec)</td>
<td>18.3</td>
<td>16.7</td>
</tr>
<tr>
<td>Range</td>
<td>-19/73</td>
<td>9/98</td>
</tr>
</tbody>
</table>

*: significant group differences (patient group vs control group) (p < 0.01)
°: significant side differences (dominant / injured side vs non-dominant / non-injured side) (p < 0.05)
Trapezius Latency in overhead athletes

Table 4: Post-hoc statistical analysis for the differences in muscle latency among the muscles:

between the middle deltoid and upper trapezius (pair UT-DM), the middle deltoid and middle trapezius (pair MT-DM), the middle deltoid and lower trapezius (pair LT-DM), the upper trapezius and middle trapezius (pair: MT-UT), the upper trapezius and lower trapezius (pair LT-UT), the middle trapezius and lower trapezius (pair LT-MT). Mean differences and p-values

<table>
<thead>
<tr>
<th>Patient group (N = 39)</th>
<th>Control group (N = 30)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non-injured side</td>
</tr>
<tr>
<td>DM-UT</td>
<td>Mean Difference 18.5</td>
</tr>
<tr>
<td>DM-MT</td>
<td>Mean Difference 23.0</td>
</tr>
<tr>
<td>DM-LT</td>
<td>Mean Difference 28.0</td>
</tr>
<tr>
<td>UT-MT</td>
<td>Mean Difference 4.5</td>
</tr>
<tr>
<td>UT-LT</td>
<td>Mean Difference 9.5</td>
</tr>
<tr>
<td>MT-LT</td>
<td>Mean Difference 5.0</td>
</tr>
</tbody>
</table>

DISCUSSION

It is generally accepted that the three trapezius parts, together with the serratus anterior, have an important function by acting as force couples providing the dynamic stability of the scapula\(^5, 19, 26, 28\). However, within these force couples, the upper, middle and lower trapezius participates in different ways\(^25\). The specific actions of the muscles around the scapulothoracic joint have been discussed by several authors\(^5, 19, 25, 39\). Johnson et al.\(^25\) described the anatomy of the trapezius muscle, and derived its possible actions based on fascicular anatomy. As the serratus anterior contracts, its force tends to draw the scapula laterally around the chest wall but this displacement is resisted by the lower fibers of trapezius which operate at constant length to stabilize the axis of rotation. The upper fibers of the trapezius then exert an upward rotation moment about the axis, complementing that of the serratus anterior. The middle trapezius fibers, although strong, lie very close to the axis of
rotation of the scapula. Therefore, their ability to generate an upward rotatory moment is compromised by relatively short moment arms. The author concluded based on his data that the middle and lower fibers maintain horizontal and vertical equilibrium of the scapula rather than generating net torque. This stabilizing role of middle and lower trapezius has also been suggested by others\textsuperscript{28, 40, 55}.

Optimal function of stabilizing muscles depends not only upon the force production of these muscles in relation to synergists, antagonists and prime movers of a joint, but also upon the correct timing of muscle activation. Although trapezius muscle dysfunction is often assumed in patients with impingement\textsuperscript{28, 38, 40}, evidence to support the existence of abnormal electromyographic patterns in people with shoulder pain is limited. Ruwe et al.\textsuperscript{46} demonstrated a decrease in upper trapezius muscle activity during swimming in competitive swimmers with shoulder pain. More recently however, an increase in muscle activity in upper and lower trapezius was demonstrated in an impingement group during humeral elevation in the scapular plane\textsuperscript{31}. These findings seem to be contradictory. However, while Ruwe et al.\textsuperscript{46} analyzed electrical muscle activity during a breaststroke in competitive swimmers, Ludewig et al.\textsuperscript{31} examined muscle activity during uniplanar elevation in the scapular plane in non-athletic patients. Both the difference in movement and in patient recruitment may explain the discrepancy between both studies. Extrapolation of the results to the present study should be performed with caution.

The temporal recruitment pattern of the trapezius muscle during voluntary shoulder abduction in the scapular plane has been examined by Wadsworth et al.\textsuperscript{55}. Results indicated that in injured shoulders all three muscles displayed significantly increased variability in the timing of activation. According to the authors, this may reflect inconsistent or poorly coordinated muscle activation.
Trapezius Latency in overhead athletes

The present studies primary interest was in comparing patients with shoulder impingement to healthy shoulders concerning the muscle recruitment patterns of the trapezius and deltoid muscles. In a previous study\textsuperscript{10}, scapular latency times were investigated in response to a sudden shoulder movement in healthy shoulders. In addition, the effect of muscle fatigue on timing of muscle activity was examined. The results of this study demonstrated a temporal recruitment pattern of glenohumeral versus scapulothoracic muscle activity, in which the glenohumeral prime mover was activated prior to stabilizing muscle activity of the trapezius muscle. Within the trapezius muscle, no significant differences where found in timing of activity, although a preference order was observed of upper – middle – lower trapezius activity. Fatigue caused a delay in all muscle latency times, but the temporal sequence of muscle activation remained unchanged.

Probably the most striking finding in this study was the observation that the patient group showed significant slower muscle activation in the middle and lower trapezius compared to the control group, on the injured as well as on the non-injured side. Moreover, analysis of relative muscle latency times showed significant differences between both groups regarding the RMLT of middle and lower trapezius. On both sides, the time between the onset of middle deltoid on one hand and the start of muscle activity in both the middle and lower trapezius was longer in the patient group as compared to the control group. In addition, the RMLT of lower trapezius was significantly longer on the injured side as compared to the non-injured side in our patient group. If the middle and lower portions of the trapezius, which are suggested to have a more stabilizing role in the scapulothoracic joint, react too slow in regard to muscle onset of upper trapezius, as shown in this study, this may lead to relative supremacy of upper trapezius. Since alteration in dominance of any muscle can compromise the muscle balance around the scapula, this may indicate an abnormality in the coordinated rotation of the scapula on the thorax (scapulohumeral rhythm). In view of the specific participation of
each muscle, as discussed by Johnson et al.\textsuperscript{25}, scapular motion during shoulder movement probably will be characterized by scapular elevation rather than acromial upward rotation. Literature has shown that changes in dynamic scapular positioning is related to shoulder dysfunction\textsuperscript{31, 32, 57}. Results of the present study support this assumption. The findings in this study are to some extent related to the findings of Janda\textsuperscript{20} regarding tonic and phasic muscles. He asserted that much musculoskeletal pain is from, in part, a chronic shortening of certain muscles which cause alterations in normal muscle activity patterns. According to this author, the upper trapezius is prone to muscle tightness, whereas the lower trapezius is a muscle prone to weakness. Theoretically, delay in muscle onset may reflect stretch weakness\textsuperscript{20}. Comparing the non-injured and the injured shoulder in the patient group, results show that in the patient group, on both sides, the deltoid muscle is active significantly prior to activation of the trapezius. This pattern also occurs on the non-dominant side of the control group. These findings are in close agreement with the results of a previous study on healthy shoulders, in which the same recruitment order of glenohumeral versus scapulothoracic muscles was found\textsuperscript{10}. However, on the dominant side of the control group, muscle latency times of deltoid muscle and middle trapezius muscle show no significant differences, suggesting that these muscles fire simultaneously in response to a sudden arm movement. This finding is verified by the fact that the RMLT, or the time from onset or deltoid muscle to onset of trapezius muscle, is significantly shorter on the dominant side of the healthy subjects as compared to the non-dominant side. This result may reflect enhanced neuromuscular control mechanisms in competitive overhead athletes compared to normal subjects, not participating in overhead sports, and compared to the non-throwing extremity. These results are similar to previous observations that neuromuscular performance characteristics vary between subjects with variations in muscle-activity levels or coordination patterns\textsuperscript{4, 15, 18, 48}. Striking however is the observation that this enhanced reaction is not present at the dominant side of the injured
shoulders in our patient group, who are also competitive overhead athletes. It seems that the patient group does not show these adaptations in neuromuscular performance, suggested on the base of athletic overhead activities.

Analysis of muscle differences between the three trapezius muscles showed significant differences between all three trapezius parts on the injured side in the patient group. In the control group, with the exception of an early activation of the middle trapezius on the dominant side, all trapezius parts fired simultaneously. This pattern was also found in our study on healthy shoulders\textsuperscript{10}. Based on the results of the control group, and the results of our previous study, we may conclude that normal muscle recruitment of trapezius muscle in response to a sudden arm movement consists of simultaneous activation of all three trapezius parts in order to sufficiently stabilize the scapula. In view of that suggestion, the alterations in the timing of trapezius muscle activity on the injured side in our patient group may reflect diminished quality of neuromuscular performance of the scapular muscles.

An interesting finding in this study is the observation that both the injured and the non-injured sides of the patient group display differences from the control group. In particular, the middle and lower portions of the trapezius were bilateral delayed in their recruitment in injured subjects. Bilateral deficits in unilaterally injured patients are also demonstrated in the neuromuscular performance of the knee\textsuperscript{61} and in glenohumeral proprioception\textsuperscript{21}. It is unclear whether this muscle pattern is a primary phenomenon, which may predispose the athlete to injury, or secondary as a result of the pain. This finding obviates the importance of bilateral rehabilitation of the scapular muscles, even though only one side may be injured.

Although this study has demonstrated a significant association between scapulothoracic muscle dysfunction and impingement symptoms, it is unclear whether this is a primary or secondary phenomenon. The possible association between glenohumeral and scapulothoracic problems has been investigated by several authors demonstrating scapular malpositioning or
abnormal scapular muscle function in patients with instability or impingement problems\textsuperscript{14, 31, 32, 33, 46, 50, 55, 57}. Some authors state that scapular malpositioning or muscle dysfunction increases the risk for shoulder impingement\textsuperscript{8, 50}, thus referring to scapulothoracic dysfunction as the primary phenomenon, while others suggest that scapulothoracic muscles are inhibited by painful conditions at the shoulder as a secondary result\textsuperscript{28}. It appears that the serratus anterior and the lower trapezius muscles are the most susceptible to the effect of the inhibition\textsuperscript{14, 42}.

The relatively low ICC’s of the testing procedure must be acknowledged as a limitation of this investigation. Indeed, although ICC of 0.70-0.89 are considered to demonstrate high correlations\textsuperscript{12}, Intraclass Correlation Coefficients of > 0.90 are recommended for clinical use\textsuperscript{13, 54}. These values possibly reflect a major concern in electromyography which is the use of surface electrodes. The current state of surface electromyography is enigmatic. Although it provides many important and useful applications, it has some limitations that must be considered\textsuperscript{11}. A major problem is the issue of the cross talk when using surface electrodes in the shoulder region. However, investigating large muscle groups such as the trapezius muscle, surface electrodes do give a more global evaluation of muscle activity than fine wire electrodes, which measure a rather small selection of muscle fibres. In addition, cross talk is not likely in our setting since Winter et al.\textsuperscript{60} estimated that 90\% of a surface EMG signal has its origin within 12-mm distance from an electrode pair.

This study highlighted a bilateral delay in muscle onset of the middle and lower trapezius in unilateral injured shoulders when compared to non-injured subjects. Clinicians should be aware of the relevance of temporal muscle recruitment patterns prescribing guidelines for shoulder rehabilitation. However, future studies are needed to determine whether alterations in muscle latency times are the cause or the consequence of injury, and to determine if these muscle recruitment patterns can be altered by rehabilitation programs.
CONCLUSION

We compared the Muscle Latency Times of the trapezius muscle between subjects with impingement syndrome and non-injured subjects in response to a sudden downward falling movement of the arm. Results showed that there were significant group differences regarding the timing of scapular muscle activity in relation to muscle onset of the deltoid muscle, and among the three trapezius parts. Compared to the non-impaired subjects, those with impingement showed a delay in muscle activation of the middle and lower trapezius muscle, and a lack of coordination between the different trapezius parts. We may conclude that overhead athletes with impingement symptoms show abnormal timely muscle recruitment in the middle and lower trapezius muscle.

The findings of this study support the theory that shoulder impingement may be related to delayed muscle onset of middle and lower trapezius, and may have implication for the non-surgical treatment of impingement syndrome.
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CHAPTER 4

TEST-RETEST REPRODUCIBILITY OF CONCENTRIC STRENGTH VALUES FOR SHOULDER GIRDLE PROTRACTION AND RETRACTION USING THE BIODEX ISOKINETIC DYNAMOMETER

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Chapter IV

ABSTRACT

The aim of this study is to determine the rest-retest reproducibility for measuring the peak torque and the total work of the protractors and retractors of the shoulder girdle according to the isokinetic concentric muscle action. The tests were performed in two sessions at a 7 day interval. Nineteen healthy volunteers were included. Evaluation was carried out with a Biodex® System 3 Isokinetic Dynamometer using the Closed Chain Attachment. The protocol consisted of 5 isokinetic concentric contractions at a linear velocity of 12.2 cm/sec and 10 repetitions at a velocity of 36.6 cm/sec. The shoulder girdle protraction and retraction movements were performed with the arm horizontal in the scapular plane, which is 30° anterior of the frontal plane. Intraclass-Correlation-Coefficients were calculated to establish day-to-day repeatability. Results show an excellent reproducibility for isokinetic peak torque at both velocities on the non dominant side (ICC 0.94 - 0.96) and very good to excellent reproducibility on the dominant side (ICC 0.88 - 0.92). Reproducibility was also very good for total work values in both movement directions at both velocities (ICC 0.82 - 0.89). The results indicate that isokinetic protraction and retraction strength evaluation is a reliable tool in the evaluation of shoulder girdle muscular performance. This may be clinically important in the assessment of shoulder dysfunction.
INTRODUCTION

Chronic shoulder pain and functional disorders are common upper extremity problems among individuals of all ages and all activity levels [1,33]. Most shoulder disorders result from cumulative overload injuries to the rotator cuff and related soft tissues [14]. In recent literature, glenohumeral tensile overload is often related to scapulothoracic dysfunction [19,45]. Because the scapula plays a critical role in controlling the position of the glenoid, relatively small changes in the action of scapulothoracic muscles can affect the alignment and forces involved in movement around the glenohumeral joint [36]. It has been hypothesized that muscular imbalance in the scapular muscles may affect shoulder function, and predispose to overload rotator cuff injury [19,45].

The objective recording of shoulder strength plays an important role both for diagnostic and rehabilitation purposes [28]. Isokinetic dynamometry is extensively used in the quantitative assessment of glenohumeral shoulder musculature [3,4,8,9,10,16,23,28,29,32,35,37]. Not only peak force values, but also agonist-antagonist ratios are considered highly useful measurements to evaluate muscular performance and muscular balance [10,45]. Previous data are available demonstrating the reliability for measuring glenohumeral muscle performance [7,11,13,24,25,27,39,42]. Reliability, however, is specific to a particular movement pattern and needs to be established for any new test methodology. To our knowledge, no literature exists regarding the isokinetic assessment of scapulothoracic muscle performance. Especially evaluation of isokinetic protraction and retraction force production deserves our attention since this measurement provides a reflection of muscle activity in the trapezius as well as in the serratus anterior [18,34]. These muscles are known to play an important role in the functional stability of the scapulothoracic joint [19,30]. The purpose of this study is to establish the day-to-day repeatability of an isokinetic testing protocol for the shoulder girdle
protractors and retractor s in the scapular plane using the Biodex® System 3 isokinetic dynamometer. In addition, since isokinetic strength values for shoulder girdle protraction and retraction are not reported in literature, side and speed differences as well as agonist/antagonist ratios are a topic of interest. Clinically, this study would provide a foundation for future quantitative research examining neuromuscular performance of the scapular muscles.

MATERIALS AND METHODS

Subjects

Nineteen healthy subjects (9 males, 10 females), without a history of shoulder pathology or ongoing neck or shoulder pain, volunteered to participate in the study. None of the subjects were familiar with isokinetic testing or were involved in overhead sports. The mean age of the study sample was 23 years (range 20-27 years). The mean and standard deviations of their height and body weight were 171.6 +/- 11.2 cm and 66.6 +/- 11.6 kg, respectively. Sixteen subjects were right handed, three left handed. All subjects signed an informed consent. The study was approved by the Ethical Committee of Ghent University.

Testing procedure.

All tests were performed using a Biodex® System 3 isokinetic dynamometer (Biodex Medical Systems, Inc., 20 Ramsay Road, box 702, Shirley, New York, U.S.A.). The subjects were
tested during two identical testing sessions held 7 days apart. The same tester administered both tests for all the subjects.

The testing session started with a warm up procedure, consisting of shoulder movements in all directions, pushup-exercises against the wall and stretching exercises for the rotator cuff and scapular muscles. Dominant and non dominant shoulders were tested in random order. The dominant hand was assigned as the hand used for writing.

For the testing procedure, the closed chain attachment was fixed to the isokinetic dynamometer in a horizontal position. Essentially, this device converts rotational motion at the dynamometer into linear motion, allowing closed kinematic chain or linear movements. The handgrip was inserted into the attachment receiving tube with the neutral handle facing up, in order to keep the glenohumeral joint in a neutral rotational position. The chair was rotated to 15 degrees and the dynamometer to 45 degrees (figure 1). The subject was assessed in the seated position with his arm horizontal in the scapular plane, which is 30° anterior of the frontal plane. The subjects were instructed to keep their elbow extended. Stabilization of the trunk was obtained using a strap diagonally from the contralateral shoulder across the chest. Each subjects was first tested at 60°/sec, followed by the second test at 180°/sec. With the velocity conversion from rotational into linear movement, this means a first test at a linear velocity of 12.2 cm/sec, followed by a second test at a linear velocity of 36.6 cm/sec. Range of motion was assessed asking the subject to perform a maximal protraction and a maximal retraction movement. Gravity correction was not performed since the movement occurs in a horizontal plane. The test started in a maximal retracted position, and the subjects were instructed to perform maximal protraction and retraction movements over the total range of motion. Five repetitions were performed at the linear velocity of 12.2 cm/sec, and after a resting period of 10 seconds, 10 repetitions at a linear velocity of 36.6 cm/sec. All subjects performed five familiarization trials prior to collecting data, and they all benefited from verbal
encouragement. Visual feedback from the computer screen was not allowed. After testing, the results were printed on a report consisting peak force and total work values and coefficients of variance. The latter value, automatically calculated by Biodex ® software, is a statistical representation of the test validity based on reproducibility of performance. It represents the variability between the five (slow velocity) or 10 (fast velocity) repetitions. Lower values represent higher reproducibility.

Figure 1: experimental setup for the evaluation of the isokinetic protraction-retraction force in the scapular plane, using the Biodex® System 3 isokinetic dynamometer with the Closed Chain attachment.

Data analysis

Descriptive statistics were used to calculate the mean peak force and mean total work values for isokinetic protraction and retraction for both testing sessions. Mean coefficients of variance were noted for all the test results. Overall mean coefficient of variance for all the tests was calculated for both testing sessions. In addition, the agonist/antagonist muscle ratio
was calculated with the protraction force as the agonist value and the retraction force as the antagonist value.

To establish between-day repeatability, Intraclass Correlation Coefficients were calculated between the peak torque and total work values in both sessions. The specific ICC used was the two-factor model for random effects (type 2,1), recommended by Shrout and Fleiss [38], as the proper ICC when the researchers wish to estimate the reproducibility of an instrument for clinical use [5,7,13]. In addition, the results were analyzed with paired t-tests to determine mean differences between the two sessions. As indicators of reliability, Standard Error of Measurement (SEM), the 95% confidence range of SEM (95% SEM), and the 95% Limits of Agreement (95% LOA) were calculated [2,15,26,31,40]. SEM was derived from the formula SEM = \( SD \times (1 - ICC)^{0.5} \) where \( SD \) was the standard deviation of the peak torque or total work data of the study sample, and ICC the calculated Intraclass Correlation Coefficient [2,40]. The 95% confidence range of SEM was calculated using the expression 95% SEM = 1.96 \times 2^{0.5} \times SD \times (1-ICC)^{0.5} where \( SD \) was the standard deviation of the peak torque or total work data of the study sample, and ICC the Intraclass Correlation Coefficient [26]. The 95% limits of agreement (95% LOA) were calculated using the expression 95% LOA = \( \bar{d} + 1.96 \times sd \), where \( \bar{d} \) and \( sd \) were the mean and standard deviation of the differences between the two sessions for average peak torque and total work data [31].

Differences in peak force, total work and agonist-antagonist ratio values were analyzed with a general linear model (GLM) 2-way ANOVA for repeated measures, in which the within factors were side (2 levels) and velocity (2 levels). Post-hoc comparisons were conducted with paired t-tests with Bonferroni correction if necessary. The alpha level was set on 0.05. All statistical analysis was performed with SPSS® for Windows ® (Version 10.0, SPSS, Inc., Chicago, IL) software.
Chapter IV

RESULTS

The descriptive analysis for the peak force (PF) and total work (TW) values for both testing sessions, with the corresponding ICC-coefficients, SEM, 95% SEM, 95% LOA, and p-values from the paired t-tests are summarized in table 1 and 2 respectively. Test-retest Intraclass Correlation Coefficient values (ICC 2,1) ranged from 0.88 to 0.97 for all peak force scores (table 1) and 0.82 to 0.90 for all total work scores (table 2) (p < 0.01). In addition, paired t-tests showed no significant differences between both testing sessions, except for the retraction peak force at slow velocity on the non-dominant side (p < 0.05). SEM-values ranged between 20.8-42.9 N for the peak force data and between 144.9-344.7 for the total work data. Intersession variability calculated using 95% SEM ranged between 57.4 – 118.4 N for the peak force data, and between 399.9-951.4 J for the total work data. Table 3 shows the Means and Standard Deviations for the agonist/antagonist ratio for both sides at both speeds. The protraction/retraction ratio varied from 0.96 (the dominant side for the test at 36.6 cm/sec in the second session) to 1.18 (the non-dominant side for the test at 12.2 cm/sec in the first session). The Mean Coefficient of Variance ranged from 8.3 (protraction at the non dominant side at slow velocity in the second session) to 17.8 (protraction at the dominant side at slow velocity in the first session). The mean overall coefficient of variance over all test movements was 14.8 in the first session, and 13.0 in the second session. Descriptives of coefficient of variance values are summarized in table 4.

Since the reproducibility of our testing procedure was high, further statistical analysis on side and speed differences was performed on the data of the second session. The two-way ANOVA for repeated measures (General Linear Model) revealed significant differences
between both testing speeds regarding the peak force values of protraction (p < 0.001) and retraction (p < 0.001), and also for the agonist/antagonist ratios (p < 0.001). We found no significant differences between the dominant and non-dominant sides (p = 0.72 for protraction and p = 0.49 for retraction). Post-hoc paired analysis showed that peak force was significantly higher (p < 0.001) at low velocity compared to the results at high velocity. The agonist/antagonist ratio was higher at low velocity (p < 0.01). Contrary to peak force values, total work values depend on the total time. Total work represents the total muscular output for all repetitions. This takes in all force produced and multiplies it by the total time. Since the number of repetitions and consequently the total time is different for both testing speeds, speed differences for total work values are obvious and thus not relevant to this investigation. Therefore post hoc analysis was not performed on these results.

**DISCUSSION**

It is well recognized that the scapula plays the scapula is clinically relevant in order to detect muscular imbalances, related to an important role in the stability and mobility of the shoulder [19,45]. Especially in sports, where the demands on the shoulder are extremely high, the quality of movement depends upon the interaction between scapular and glenohumeral kinematics. Abnormal scapular kinematics and associated muscle function presumably contribute to shoulder pain and pathology [1,30,33]. Hence, the muscular control of the scapula has become a recent focus of therapeutic intervention [19,22,45]. Therefore, objective assessment of muscle performance around shoulder dysfunction [28]. The purpose of this study was to establish the day-to-day repeatability of the testing protocol evaluating the isokinetic shoulder girdle protraction and retraction muscle force in the
scapular plane. In addition, side differences and agonist/antagonist ratios were evaluated in this investigation.

We found ICC coefficients for the peak force production between 0.88 (peak force for protraction and retraction at a velocity of 12.2 cm/sec at the dominant side) and 0.97 (peak force for retraction at a velocity of 12.2 cm/sec on the non-dominant side). Intra Class Correlation Coefficients for the total work values are found to be between 0.82 (total work for retraction at 12.2 cm/sec on the dominant side) and 0.90 (total work for protraction at 36.6 cm/sec on the dominant side). According to Fleiss [12], good reliability is demonstrated by an ICC of > 0.75. Intraclass Correlation Coefficients of > 0.90 are considered to have excellent reliability for clinical use [2,12,43]. Thus, the results of the present study support the hypothesis that our testing protocol on the Biodex® isokinetic dynamometer is a reliable tool in evaluating the peak force and total work of shoulder girdle strength. Establishing the reliability of a new technique as presented here is a prerequisite for future investigations regarding the muscle performance of shoulder girdle protraction and retraction, as well in an athletic as in a patient population.

In recent literature, the use of the Intraclass Correlation Coefficient is no longer recognized as the best way to assess reproducibility [2,15,26,31,40]. ICC is prone to the same constraints as Pearson’s r, in that it includes the variance term for individuals and is therefore affected by sample heterogeneity to such a degree that a high correlation may still mean unacceptable measurement error for some analytical goals [2]. Therefore, SEM, 95% SEM and 95% LOA offer additional relevant information to adequately assess the reproducibility of a procedure. These statistics express measurement error in the same units as the original measurement, and are not influenced by variability among patients [40]. Therefore, peak force and total work values should be interpreted with caution in clinical circumstances, using SEM and LOA as guidelines in patient evaluation.
We found no significant differences regarding the peak force and total work values between the dominant and non-dominant side. Similar findings based on normal, non-athletic subjects did not indicate any effect of dominance on shoulder external-internal rotation, abduction-adduction and flexion-extension strength [17,23,32,35,37]. However, care should be taken when interpreting bilateral strength ratios of athletes who use their upper limbs in an asymmetrical manner. It is known that participation in athletic activities does account for significant bilateral performance differences [4,8,9,29].

In this study, significant lower strength values were found during testing at higher velocity (36.6 cm/sec) with respect to the values at lower velocity (12.2 cm/sec). This finding is in concordance with the general agreement in literature that there is a drop in peak isokinetic torque with increasing speed [3,8,17].

In our investigation, agonist/antagonist ratios were 1.11 and 1.18 for the dominant and non-dominant side respectively at slow velocity, and 0.96 and 1.05 respectively at high velocity. This means that protraction force is slightly higher than retraction force when the movements are performed at a slow velocity. At high velocity, both movements are equal in strength, with a moderate preponderance for the retraction force on the dominant side. Wilk et al.[45] documented the isometric scapular muscle strength values of professional baseball players. The values ranged from 1.02 to 1.24. In addition, the results indicated that on the dominant side, the players exhibited a lower protraction/retraction ratio when compared to the non-dominant side. Our results show slightly lower values for protraction/retraction ratios with less side differences compared to the study of Wilk et al. [45]. However, the population studied by Wilk et al. [45] was involved in overhead sports, whereas our population consisted of normal, healthy non-athletic subjects. Moreover, we examined isokinetic muscle strength, where isometric muscle performance was evaluated in the Wilk study [45]. Comparisons between both studies should be interpreted with caution.
Since we used the closed chain attachment for our investigation, it seems appropriate to discuss literature investigating reliability and reproducibility of other linear isokinetic observations. Levine et al. [21] performed a test-retest reliability study on a closed chain leg extension protocol and reported ICC values between 0.80 and 0.96. A leg stretching movement at 40 cm/sec was found to be reliable using a test-retest method on a Cybex® isokinetic dynamometer (ICC 0.89-0.96) [46]. Davies & Heiderscheit [6] reported an ICC of 0.87-0.94 using a Lido Linea closed kinetic chain isokinetic dynamometer during a leg press pattern. In a recent study [20], a high reliability (ICC 0.85-0.99) was found for the measurement of mean force and power of the total lifting movement with the upper limbs and of the sitting leg extension movements, performed on a Aristokin® linear isokinetic dynamometer. With ICCs ranging from 0.80 to 0.97, this present study had similar results to other studies investigating linear isokinetic testing.

We preferred to perform the isokinetic testing in a shoulder position of 90° elevation in the scapular plane, which is 30° anterior of the frontal plane instead of performing protraction and retraction movements in the coronal plane. Research has suggested that isokinetic assessment of muscle performance in patients with shoulder pain should be performed in the scapular plane, rather than in the coronal or frontal plane [5,7,22,25,41,44]. This arm position reduces the stress placed on the anterior capsuloligamentous structures, and prevents impingement of the rotator cuff under the acromion. It also provides better congruency between the articular surfaces of the glenohumeral joint, and offers more comfort to the injured subject. Moreover, the scapular plane is thought to be a more functional plane for daily and athletic activities.

There are several limitations of this study including (1) the limited sample size, precluding extrapolation of our results to normative data for a larger population, and (2) the fact that only uninjured non athletic subjects were evaluated, which precludes extrapolation of the results to an athletic or patient population. Further studies are needed to examine the reliability of the
procedure in an athletic and in a patient population. In future investigations, normative data from a large sample of healthy subjects should be determined as a reference base for the rehabilitation of scapular function in patients with shoulder pain.

CONCLUSION

The Biodex® System 3 isokinetic dynamometer was found to be a reliable tool for measuring concentric shoulder girdle protraction and retraction in the scapular plane on healthy, non-athletic subjects. This new test may be clinically relevant in the objective evaluation of shoulder girdle muscle performance. Muscular imbalances in the scapular muscles are often seen in patients with shoulder pathology. Assessment of isokinetic muscle performance of the scapular protractors and retractors may add valuable information to provide rehabilitation guidelines to the patient.
Table 1: Mean and Standard Deviations (SD) for the Peak Force (PF) (Newton) of shoulder girdle protraction (PRO) and retraction (RET) at a linear speed of 12.2 cm/sec (SLOW) and 36.6 cm/sec (FAST) at the non-dominant side (ND) and dominant side (D)(N=19). The corresponding values for Intraclass Correlation Coefficient (ICC), Standard Error of Measurement (SEM), 95% confidence range of SEM (95% SEM), p-values from paired t-tests, and 95% limits of agreement (95% LOA) are also presented.

(*: p < 0.05)

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<th>Day 1</th>
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<th>t-test p-value</th>
<th>95% LOA (N)</th>
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Table 2: Mean and Standard Deviations (SD) for the Total Work (TW) (Joule) of shoulder girdle protraction (PRO) and retraction (RET) at a linear speed of 12.2 cm/sec (SLOW) and 36.6 cm/sec (FAST) at the non-dominant side (ND) and dominant side (D)(N=19). The corresponding values for Intraclass Correlation Coefficient (ICC), Standard Error of Measurement (SEM), 95% confidence range of SEM (95% SEM), p-values from paired t-tests, and 95% limits of agreement (95% LOA) are also presented.

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<td>344.7</td>
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Table 3: Mean and Standard Deviations (SD) for the agonist/antagonist ratio (RATIO) at a linear speed of 12.2 cm/sec (SLOW) and 36.6 cm/sec (FAST) at the non-dominant side (ND) and dominant side (D) (N=19)

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<th>Day 2</th>
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<td>SD</td>
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<td>0.18</td>
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<tr>
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<td>0.17</td>
<td>1.02</td>
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</tr>
<tr>
<td>RATIO-SLOW-D</td>
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<td>0.22</td>
<td>1.11</td>
<td>0.19</td>
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<tr>
<td>RATIO-FAST-D</td>
<td>1.00</td>
<td>0.20</td>
<td>0.96</td>
<td>0.17</td>
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</tbody>
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Table 4: Mean and Standard Deviations (SD) for the Coefficient of Variance (COV) for shoulder girdle protraction (PRO) and retraction (RET) at a linear speed of 12.2 cm/sec (SLOW) and 36.6 cm/sec (FAST) at the non-dominant side (ND) and dominant side (D) (N=19). The overall Coefficient of Variance (over all test movements) is also presented.

<table>
<thead>
<tr>
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<td>SD</td>
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</tr>
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REFERENCES


CHAPTER 5

EVALUATION OF ISOKINETIC FORCE PRODUCTION AND ASSOCIATED MUSCLE ACTIVITY IN THE SCAPULAR ROTATORS DURING A PROTRACTION-RETRACTION MOVEMENT IN OVERHEAD ATHLETES WITH IMPINGEMENT SYMPTOMS

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Chapter V

ABSTRACT

Objectives: In this single group bilateral comparison of isokinetic shoulder girdle strength and electromyographic activity in the scapular rotators 19 overhead athletes with impingement symptoms were studied to determine if the muscle force and electromyographic activity in the scapular rotators at the injured side showed differences compared to the non injured side. Scapulothoracic dysfunction has been suggested to be related to shoulder impingement. Therefore, objective quantification of muscle strength and associated electromyographic activity should be studied in this patient group.

Methods: Isokinetic peak force was evaluated for protraction and retraction movement of the shoulder girdle, with simultaneous registration of electromyographic activity of the three trapezius parts and the serratus anterior muscle.

Results: Paired t-tests showed significant lower peak force at the injured side for isokinetic protraction at high velocity (p<0.05), a significant lower protraction/retraction ratio (p<0.01), and significant lower electromyographic activity in the lower trapezius part during isokinetic retraction at the injured side, compared to the non injured side (p<0.05).

Conclusion: These results confirm the hypothesis that patients with impingement symptoms show abnormal muscle performance at the scapulothoracic joint
INTRODUCTION

The shoulder plays a vital role in many athletic activities. Overhead motions such as throwing, swimming, and serving in tennis repetitively place the shoulder in vulnerable positions possibly leading to impingement syndrome. This syndrome has been classified as primary or secondary. Primary impingement refers to mechanical encroachment into the subacromial space by the humeral head, often seen in middle-aged patients\(^1,2,3,4,5\). Secondary impingement syndrome symptoms are thought to be a result of shoulder instability, posterior capsule tightness and scapulothoracic weakness, which may contribute to functional shoulder instability\(^2,6,7\). Functional shoulder instability has been defined as the clinical situation in which the pathology does not allow the humeral head to move excessively relative to the confines of the glenoid fossa or to pass over the rim as in a subluxation of dislocation (anatomical glenohumeral instability). However, overall lax or overstretched glenohumeral ligaments intermittently jeopardize normal shoulder function\(^8\). The patient feels he cannot trust or control the stability of his shoulder, hence the designation “functional shoulder instability”\(^9\). It is now thought that functional instability in the shoulder may be one of the causes leading to a vicious circle involving microtrauma and secondary impingement, and may eventually lead to chronic shoulder pain\(^10\).

Many muscles attach to the scapula, some act as scapular rotators; others are concerned with glenohumeral movement. The major upward rotators of the scapula are the upper and lower fibres of trapezius and the lower digitations of serratus anterior\(^2,11\). Most authors\(^12,13,14\) agree that weakness in one or more scapular rotators may cause a relative muscular imbalance in the force couples around the scapula, thus leading to abnormal kinematics. Scapulothoracic dysfunction is often seen in patients with shoulder problems\(^2,12,13,14,15,16,17,18,19,20,21,22\). In a recent study\(^22\), the authors found that overhead athletes with impingement symptoms showed
abnormal timely muscle recruitment in the trapezius muscle. The most striking finding in this study was the observation that, in response to a sudden arm movement, the patient group showed significant slower muscle activation in the middle and lower trapezius compared to the control group, on the injured as well as on the non-injured side.

A current belief is that weakness of the scapular musculature will affect normal scapular positioning. It has been suggested that, if excessive motion of the scapula occurs, this may place increased stress on the glenohumeral capsular structures and lead to increased glenohumeral instability. Malpositioning of the scapula for any given arm configuration may also influence the instantaneous centre of shoulder rotation, which can significantly alter moments of force generation about the shoulder.\(^\text{23}\).

Isokinetic evaluation of muscle performance is commonly used in the assessment of muscle performance in healthy and injured athletes. Especially the evaluation of isokinetic glenohumeral external and internal rotation movements is considered a relevant tool to investigate muscle performance in injured shoulders.\(^\text{24,25}\) However, these investigations do not reflect the quality of scapulothoracic muscle performance. Recently, the use of an isokinetic protocol was introduced to evaluate muscle performance of shoulder girdle protractors and retractors, using the Biodex® isokinetic dynamometer.\(^\text{26}\) In addition, the use of electromyography has been considered as a valuable tool to investigate the neuromuscular performance in healthy and injured shoulders.\(^\text{27,28,29}\)

The aim of this study was to investigate the isokinetic muscle performance of the shoulder girdle protractors and retractors, with simultaneous registration of electromyographic activity in the scapular muscles in overhead athletes showing symptoms of impingement.
METHODS

Subjects

Nineteen overhead athletes (14 males, 5 females) with unilateral shoulder pain on the dominant side were included in this report. The average age was 21.9 years (range: 18-25). Thirteen patients were volleyball players, 3 tennis players, and 3 athletes from other overhead sports. All subjects completed questionnaires about their history of shoulder pain, their training and athletic performance history.

A shoulder with symptoms of shoulder impingement was determined by history and confirmed by physical examination to check for signs of impingement (Neer, Hawkins, supraspinatus test, apprehension and relocation test). Patients were included in the impingement group if they had at least 2 of the following 5 criteria:\textsuperscript{19,22,30,31}:

1. Positive Neer sign: reproduction of pain when the examiner passively flexes the humerus to end-range with overpressure.
2. Positive Hawkins’ sign: reproduction of pain when the shoulder is passively placed in 90° forward flexion and internally rotated to end-range.
3. Positive Jobe’s sign: reproduction of pain and lack of force production with isometric elevation in the scapular plane in internal rotation (empty can)
4. Pain with apprehension: reproduction of pain when an anteriorly directed force is applied to the proximal humerus in the position of 90° of abduction and 90° of external rotation
5. Positive relocation: reduction of pain after a positive apprehension test when a posteriorly directed force is applied to the proximal humerus in the position of 90°/90°.

For inclusion, at least one impingement sign needed to be positive, with in addition a second positive impingement test or a painful apprehension / positive relocation test\textsuperscript{22}. It is thought
that patients with minor instability and secondary impingement will experience pain, but not apprehension with these tests\textsuperscript{10,32}. Although not agreed upon in literature, these tests currently are considered to be valuable in the clinical evaluation of symptoms associated with impingement\textsuperscript{10,32}

Subjects were excluded if they had a history of dislocation of the shoulder, shoulder surgery, current symptoms related to the cervical spine, or documented structural injuries to the shoulder complex. All subjects gave their written informed consent to participate in this study. The study was approved by the Ethical Committee of the Ghent University.

\textbf{Testing procedure}

\textit{Electromyographic recording}

Prior to electrode application, the skin was prepared with alcohol to reduce skin impedance (typically < 10 kOhm). Bipolar surface electrodes (Blue Sensor® – Medicotest, Denmark) were placed with a 1 cm inter-electrode distance over the upper, middle and lower portions of the trapezius muscle and the lower portion of the serratus anterior, according to the instructions of Basmajian\textsuperscript{33}. A reference electrode was placed over the clavicle. Each set of bipolar recording electrodes from each of four muscles was connected to a Noraxon Myosystem 2000® electromyographic receiver (Noraxon USA, Inc., Scottsdale, AZ). The sampling rate was 1000Hz. All raw myo-electric signals were preamplified (overall gain = 1000, common rate rejection ratio 115 dB, Signal to Noise Ratio <1 µV RMS baseline noise, filtered to produce a bandwidth of 10-1000 Hz). Measurements from the Biodex® dynamometer and electromyographic recordings were fully synchronised through the analog input of the EMG-receiver. Both electromyographic signals and movement direction/isokinetic force production were stored by the Myoresearch® software program.
Prior to isokinetic testing, verification of EMG signal quality was completed for each muscle by having the subject perform isometric contractions in manual muscle test positions specific to each muscle of interest. Subjects performed three 5-second maximum voluntary isometric muscle contractions against manual resistance by the principal investigator. A 5-second pause occurred between muscle contractions. As a normalisation reference, EMG data were collected during Maximal Voluntary Contraction (MVC) for each muscle. After signal filtering with a low-pass filter (single pass, Butterworth, 6 Hz low pass filter of the 6th order) and visual inspection for artefacts, the peak average EMG value over a window of 1 sec was calculated for each trial. Further calculations were performed with the mean of the repeated trials as a normalisation value (100%).

**Isokinetic evaluation**

All tests were performed using a Biodex® System 3 isokinetic dynamometer (Biodex Medical Systems, Inc., 20 Ramsay Road, box 702, Shirley, New York, U.S.A.). The testing session started with a warm up procedure, consisting of shoulder movements in all directions, push up-exercises against the wall and stretching exercises for the rotator cuff and scapular muscles. The non-injured shoulder was tested first, followed by the injured shoulder. For the testing procedure, the closed chain attachment was fixed to the isokinetic dynamometer in a horizontal position. The handgrip was inserted into the attachment receiving tube with the neutral handle facing up, in order to keep the glenohumeral joint in a neutral rotational position. The chair was rotated to 15 degrees and the dynamometer to 45 degrees (figure 1). The subject was assessed in the seated position with his arm horizontal in the scapular plane, which is 30° anterior of the frontal plane. The subjects were instructed to keep their elbow extended. Stabilisation of the trunk was obtained using a strap diagonally from the contralateral shoulder across the chest. Each subject was first tested at 12.2 cm/sec.
(angular velocity of 60°/sec), followed by the second test at 36.6 cm/sec (angular velocity of 180°/sec). Range of motion was assessed asking the subject to perform a maximal protraction and a maximal retraction movement. Gravity correction was not performed since the movement occurs in a horizontal plane. The test started in a maximal retracted position, and the subjects were instructed to perform maximal protraction and retraction movements over the total range of motion. Five repetitions were performed at the linear velocity of 12.2 cm/sec, and after a resting period of 10 seconds, 10 repetitions at a linear velocity of 36.6 cm/sec. All subjects performed five familiarisation trials prior to collecting data, and they all benefited from verbal encouragement. Visual feedback from the computer screen was not allowed. After testing, the results were printed on a report consisting peak force and total work values. In a previous study, the test-retest reproducibility of this procedure was found to be good to excellent for the peak force values (ICC 0.88 – 0.96), and very good for total work values (ICC 0.82 – 0.89)\textsuperscript{26}.

*Figure 1: experimental set-up for the isokinetic and electromyographic testing procedure.*
Electromyographic signal processing

All raw EMG signals were analogue/digital (A/D) converted (12-bit resolution) at 1000Hz. Signals then were digitally full-wave rectified and low-pass filtered (single pass, Butterworth, 6 Hz low pass filter of 6th order). Results were normalised to the maximum activity observed during the maximal voluntary trials. After rectifying, filtering and normalisation, further analysis was performed on five periods for each movement direction at slow velocity and 10 periods for each movement direction at high velocity. Periods were defined by markers, automatically placed on the EMG signal, thus defining a protraction or a retraction movement. The mean amplitude EMG signal, expressed as a percentage of maximal voluntary contraction, was used to assess the activity of the three trapezius parts and serratus anterior muscle in each movement direction, at both linear velocities.

Statistical analysis

Means and standard deviations were calculated for all dependent variables, namely Isokinetic Peak Force (PF) for protraction and retraction, electromyographic activity of upper trapezius (UT), middle trapezius (MT), lower trapezius (LT), and serratus anterior (SA), expressed as percentage of Maximal Voluntary Contraction during isokinetic protraction and protraction, both at slow and high velocity. In addition, the agonist/antagonist muscle ratio was calculated for both sides with the protraction force as the agonist value and the retraction force as the antagonist value.
Since all data were normally distributed with equal variances, parametric tests were used for statistical analysis. Differences in Isokinetic Peak force and scapular rotator EMG-activity between the injured and the non-injured side were analysed with paired t-tests. The alpha-level was set on 0.05. All statistical analysis was performed with the Statistical Package for Social Sciences (SPSS), version 10.0.

RESULTS

The results of the descriptive statistical analyses are summarised in table 1 for the Isokinetic Peak Force values and agonist/antagonist ratios at both speeds for both sides, in table 2 for the electromyographic activity of the three trapezius muscles and serratus anterior during isokinetic protraction at both speeds for both sides, and in table 3 for the electromyographic activity of the same muscles during isokinetic retraction.

The statistical analysis with paired t-tests revealed significant lower isokinetic protraction peak force at the injured side at high velocity (p < 0.05) compared to the non-injured side, a significant lower protraction/retraction ratio at slow velocity for the injured shoulder (p < 0.01), and significant less EMG activity in the lower trapezius part during isokinetic retraction at high velocity on the injured side (p < 0.05).
Table 1: Mean (± Standard Deviation) for the Peak Force (PF) during isokinetic protraction and retraction movements at slow (12.2 cm/sec – 5 repetitions) and high (36.6 cm/sec – 10 repetitions) velocity, and agonist/antagonist ratios. (N = 19). The corresponding p-value for the t-test between the injured and non-injured side is also mentioned.

*: p < 0.05.

<table>
<thead>
<tr>
<th>PROTRACTION (N)</th>
<th>RETRACTION (N)</th>
<th>PROTRACTION/RETRACTION RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non-injured</td>
<td>Injured</td>
</tr>
<tr>
<td>12.2 cm/sec</td>
<td>359.2 (±113.1)</td>
<td>346.8 (±114.2)</td>
</tr>
<tr>
<td>36.6 cm/sec</td>
<td>286.1 (±91.4)</td>
<td>237.9 (±85.6)</td>
</tr>
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</table>

Table 2: Mean (± Standard Deviation) for the Electromyographic activity of upper trapezius (UT), Middle Trapezius (MT), Lower Trapezius (LT) and Serratus Anterior (SA), expressed as percentage of Maximal Voluntary Contraction during isokinetic protraction movements (PRO) at slow (12.2 cm/sec – 5 repetitions) and high (36.6 cm/sec – 10 repetitions) velocity. (N = 19). The corresponding p-value for the t-test between the injured and non-injured side is also mentioned.

*: p < 0.05.

<table>
<thead>
<tr>
<th>PRO</th>
<th>UT (% MVC)</th>
<th>MT (% MVC)</th>
<th>LT (% MVC)</th>
<th>SA (% MVC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non-injured</td>
<td>Injured</td>
<td>p-value</td>
<td>Non-injured</td>
</tr>
<tr>
<td>12.2 cm/sec</td>
<td>12.9 (±8.5)</td>
<td>13.4 (±7.3)</td>
<td>0.81</td>
<td>12.8 (±6.6)</td>
</tr>
<tr>
<td>36.6 cm/sec</td>
<td>12.0 (±7.2)</td>
<td>11.8 (±6.1)</td>
<td>0.92</td>
<td>12.4 (±6.4)</td>
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</table>

Table 3: Mean (± Standard Deviation) for the Electromyographic activity of upper trapezius (UT), Middle Trapezius (MT), Lower Trapezius (LT) and Serratus Anterior (SA), expressed as percentage of Maximal Voluntary Contraction during isokinetic retraction movements (RET) at slow (12.2 cm/sec – 5 repetitions) and high (36.6 cm/sec – 10 repetitions) velocity. (N = 19). The corresponding p-value for the t-test between the injured and non-injured side is also mentioned.

*: p < 0.05.

<table>
<thead>
<tr>
<th>RET</th>
<th>UT (% MVC)</th>
<th>MT (% MVC)</th>
<th>LT (% MVC)</th>
<th>SA (% MVC)</th>
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<td>Injured</td>
<td>p-value</td>
<td>Non-injured</td>
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<tr>
<td>12.2 cm/sec</td>
<td>37.3 (±17.8)</td>
<td>36.3 (±13.3)</td>
<td>0.83</td>
<td>23.7 (±16.1)</td>
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<td>36.6 cm/sec</td>
<td>45.0 (±16.1)</td>
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<td>0.62</td>
<td>25.5 (±16.7)</td>
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DISCUSSION

The purpose of this retrospective study was to investigate two aspects of motor control about the shoulder girdle, namely isokinetic protraction and retraction force production and associated muscle activity in the scapular muscles, and to identify any deficits in these parameters in overhead athletes with shoulders impingement symptoms, compared to their contralateral non-injured side.

In our investigation, peak force values for isokinetic protraction ranged from 237.9N to 369.2N, depending on the movement velocity and on the side tested. These values are slightly higher than the values obtained in a previous study on normal subjects. However, in the previous study, normal, non-athletic subjects were evaluated in order to establish day-to-day repeatability of the procedure. Probably, the higher values obtained in this study reflect overall enhanced muscle performance in overhead athletes compared to non-athletic subjects. Striking however is the observation that, contrary to the study on healthy subjects, in which no significant differences were found between the dominant and the non-dominant side, the injured shoulders in the present study show significant lower protraction peak force at high velocity. Since, to our knowledge, isokinetic shoulder girdle muscle performance has not been investigated in shoulder patients, we have no experimental data to compare our results with. However, several authors have emphasised the importance of scapula protraction during throwing movements. Especially during the acceleration phase, the serratus anterior concentrically protracts the scapula as the arm is adducted and internally rotated. As acceleration proceeds, the scapula must protract in a smooth fashion laterally and then anteriorly around the thoracic wall to allow the scapula to maintain a normal position in relationship to the humerus, thus improving dynamic glenohumeral stability. Decreased protraction force may compromise this functional shoulder stability and hence lead to tensile
overload in the glenohumeral joint. In addition, it is suggested that the scapulothoracic muscles may be inhibited by painful conditions around the shoulder. It appears that the serratus anterior muscle and the lower trapezius muscles are the most susceptible to the effect of inhibition\textsuperscript{3,12,14,20}. Our results confirm that hypothesis. The observation that force output differences for the protraction movement are only found in the testing condition at high velocity deserves our special attention. It seems that the serratus anterior lacks power rather than absolute muscle strength. Indeed, the slower speeds, 30 to 120°/sec, have been defined as those of strength, while the faster speeds, 120 to 300 °/sec, have been defined as power\textsuperscript{38}. This ascertained may have some clinical implications, determining treatment goals in overhead athletes with impingement symptoms.

The results of this study revealed significant lower agonist/antagonist ratio on the injured side (0.97), compared to the non-injured side (1.05). In a previous study on healthy, non-athletic subjects, protraction/retraction ratios were found to be 1.11 and 1.18 for the dominant and non-dominant side respectively at slow velocity. These values are slightly higher than the ratios found in the present investigation. However, the population studied in the previous investigation consisted of healthy non-athletic subjects, whereas our population was involved in overhead sports. Wilk et al.\textsuperscript{39} documented the isometric scapular muscle strength values of professional baseball players. The values ranged from 1.02 to 1.24. In addition, the results indicated that on the dominant side, the players exhibited a lower protraction/retraction ratio when compared to the non-dominant side. Our results show slightly lower values for protraction/retraction ratios compared to the study of Wilk et al.\textsuperscript{39}, but are in concordance regarding the side differences. However, Wilk et al.\textsuperscript{39} investigated professional baseball players without shoulder problems. Moreover, we examined isokinetic muscle strength, where isometric muscle performance was evaluated in the Wilk\textsuperscript{39} study. Comparisons between both studies should be interpreted with caution.
Analysis of electromyographic muscle activity in the scapular muscles during isokinetic movements revealed a significant decrease in muscle activity in the lower trapezius during retraction on the injured side compared to the non-injured side. This finding may reflect a muscular imbalance among the three trapezius parts, since these side differences are not established in the upper and middle trapezius parts, and there were no side differences in the force output. In a previous study, a similar muscle imbalance in the trapezius muscle, with a temporal delay in muscle activity in the lower trapezius was demonstrated in overhead athletes with impingement symptoms \(^{22}\).

The significant side differences, obtained in this investigation, may reflect muscle imbalance in the scapular force couple. Since alteration in dominance of any muscle can compromise the muscle balance around the scapula, this may indicate an abnormality in the coordinated rotation of the scapula on the thorax (scapulohumeral rhythm). For example, elevation of the acromion is imprecise without the guidance and control of the lower trapezius and rhomboidei \(^{2,14,40}\).

Although the results of this study may be considered clinically relevant, several aspects of normal scapular function are not examined in this investigation. The testing position, in which the patient is sitting with his arm elevated horizontal in the scapular plane, lacks some functional relevance since gravity is eliminated and force dependent muscle activation patterns of the trunk are not facilitated. In addition, only concentric force values were obtained. However, eccentric force output and electromyographic activity are relevant muscle performance variables, especially in the overhead throwing motion \(^{14,32}\). Particularly the lower trapezius is important in its eccentric role in shoulder protraction \(^{17,39}\). Future research directions should emphasise these functional muscle performance parameters.

This study highlighted isokinetic muscle force and associated muscle activity regarding the protraction and retraction movements in the scapular plane in patients suffering from shoulder...
impingement. Future research is necessary to evaluate this parameters in overhead athletes without impingement symptoms as a reference base for clinical evaluation and rehabilitation of scapular function in patients with shoulder pain.

CONCLUSIONS

We compared the isokinetic shoulder girdle muscle force and associated electromyographic activity in the scapular muscles between the painful and non-injured shoulders in overhead athletes with impingement symptoms on their dominant side. Results showed that there were significant side differences regarding the protraction muscle force, suggesting muscle weakness in the serratus anterior muscle, and decreased electromyographic activity in the lower trapezius during isokinetic retraction, suggesting muscle imbalance in the stabilising force couple around the scapula. However, extrapolation of the results of this study to the clinical situation of overhead activity should be performed with caution, and future investigations should emphasise eccentric scapular muscle activation patterns in functional throwing positions.

The findings of this study support the hypothesis that shoulder impingement may be related to scapulothoracic dysfunction, and may have implications for the conservative treatment of impingement syndrome.
REFERENCES

CHAPTER 6

GENERAL DISCUSSION
DISCUSSION, CLINICAL IMPLICATIONS AND FUTURE DIRECTIONS

Discussion

Athletes involved in repetitive overhead activities place unique demands upon the shoulder girdle\(^2\). Overhead activities such as throwing, tennis or volleyball place the athlete at considerable risk of overuse injuries\(^{29,57}\). The glenohumeral joint is inherently unstable, and stability is provided predominantly by the ligamentous, capsular and muscular structures, and by the relative position of the glenoid and the arm throughout all arm motions\(^{64}\). These dynamic constraints include not only the dynamic musculotendinous units of the rotator cuff, but also the force couples provided by the scapulothoracic muscles\(^3^{1,66}\). The quality of neuromuscular control around the scapula depends on several parameters, determining the muscle balance of the scapular muscles. This muscular balance consists of balanced \emph{timing} of muscle recruitment, balanced \emph{force production}, and balanced muscle \emph{activity} in the scapular muscles\(^3^{1,36,40,66}\). Disturbances in scapulothoracic muscle balance have often been suggested in the literature\(^3^{1,36,60,66}\). They result in scapular instability, potentially increase the risk of shoulder problems, and would be present in timing properties as well as in force output and proportional electromyographic activity. These variables have not yet been studied, neither in a healthy population, nor in a population of overhead athletes with shoulder problems. Hence, the main objectives of this doctoral dissertation were to examine the timing, force output and muscle activity of the scapulothoracic muscles in healthy shoulders and in overhead athletes with impingement symptoms at their dominant shoulder.
The first goal of our study\textsuperscript{9} (\textit{Chapter II}) was to investigate the timing of scapulothoracic muscle recruitment. Since this had not yet been performed, a new testing protocol had to be developed and its reliability had to be tested. The results of this investigation showed that test-retest reliability of our procedure was acceptable (ICC 0.71-0.78). This study revealed a specific characteristic scapular recruitment pattern in response to sudden arm movement, which was characterised by simultaneous contraction of all three trapezius parts, initiated significantly after onset of deltoid muscle activity.

It has been suggested in the literature that timing properties of a muscle may be altered by fatigue, thus increasing the risk of fatigue-related injuries\textsuperscript{68}. Scapular muscle fatigue during rigorous exercise or physical labour may decrease the potential of dynamic stabilisation\textsuperscript{1,7,36,48,61}. However, this hypothesis has not yet been confirmed by experimental data. The results of our first study\textsuperscript{9} (\textit{Chapter II}) showed that the scapular muscle responses were considerable slower in the presence of fatigue, but the temporal sequence of muscle recruitment remained unchanged. Based on these results, we concluded that in healthy, non-athletic shoulders, the three trapezius parts react as a unit in response to sudden perturbation, and that muscular fatigue affects the onset of muscle activity, without altering the temporal sequence. Although not statistical significant, a preferential recruitment order was observed, in which the upper trapezius was activated prior to the middle and the lower trapezius. This recruitment order suggests that, in response to unexpected sudden movement, the upper trapezius reacts to move the scapula into an upward rotation (since the perturbation itself indirectly causes a downward rotation movement of the scapula), whereas the lower trapezius stabilises the scapula and regulates its smooth motion. This suggestion is consistent with hypotheses\textsuperscript{30,36,41,42} and experimental data\textsuperscript{3,44,52} available in the literature regarding scapulothoracic muscle function. In addition, the results revealed that fatigue of the scapulothoracic muscles did cause a delay in muscle reaction times, but the intermuscular
order of activation was not altered. After fatigue, the same preferential recruitment order was observed as in the pre-fatigue condition. However, comparisons between our results and functional activation patterns during throwing motions should be performed with caution, since the recruitment order is typical for the conditions of this specific investigation.

In a second study (Chapter III), we applied the muscle latency testing protocol to an athletic population with unilateral shoulder pain and to a matched control group. The most striking results of this study were: (1) overhead athletes with impingement symptoms show a significant delay in trapezius latency, especially in the lower trapezius, (2) these alterations in muscle recruitment are present both on the injured and non-injured side, (3) alterations in muscle recruitment not only occur among the three parts of the trapezius, but a delay in trapezius latency in relation to muscle onset in the prime mover (the deltoid) of the glenohumeral joint is also observed. These results provide the first experimental evidence for altered reactional temporal recruitment patterns of the scapular muscles in patients with shoulder problems. They confirm the previously described hypothesis that muscle activation of the lower trapezius is altered in overhead athletes with shoulder pathology.

The effects of altered scapular muscle recruitment on scapulothoracic motion remain unclear. It has been suggested that correct timing of muscle activity is imperative for joint stabilisation, smooth coordinated movement and injury protection. Consequently, delay in muscle onset of the lower trapezius may influence the quality of the scapulohumeral rhythm, thus causing scapular instability, and jeopardize the functional glenohumeral joint stability. According to Johnson et al., the lower trapezius regulates the scapular motion by counteracting the protraction movement provoked by the serratus anterior. A delay in activation of this muscle may lead to increased protraction with a lack of upward rotation of the scapula. This altered movement pattern would increase the risk of subacromial
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impingement\textsuperscript{20,32,36,62}. An association between temporal muscle recruitment and position properties has been established in the patellofemoral joint\textsuperscript{54}. Since similar biomechanical investigations of the association between altered muscle reaction times of the scapular muscles and changes in position and movement of the scapula have not yet been performed in the scapulothoracic joint, the consequence of altered muscle timing on scapular position remains unclear.

In addition to an examination of the timing of the scapulothoracic muscles, the second objective of this doctoral dissertation was to obtain a better insight into the force production and electromyographic muscle activity in the scapular muscles during isokinetic shoulder girdle protraction and retraction movements. For that purpose, since evaluation of isokinetic muscle performance in the scapulothoracic joint had not yet been performed, a new evaluation protocol was developed, consisting of isokinetic shoulder girdle movements with simultaneous recording of EMG activity in the scapular muscles. Consequently, in the third study\textsuperscript{11} (Chapter IV) shoulder girdle protraction-retraction movements were evaluated with an isokinetic dynamometer, in order to establish the reliability. The reliability of this procedure was found to be very high (ICC 0.82-0.96), which makes the protocol suitable for clinical and scientific use.

In the last investigation of in this dissertation\textsuperscript{13} (Chapter V), this protocol was applied to overhead athletes with impingement symptoms. In addition, the electromyographic activity in the serratus anterior and trapezius muscles during an isokinetic protraction-retraction movement was recorded. The results of this study revealed that, compared to the non-injured side, the painful shoulders showed a significant decrease in force output during the protraction movement, when tested at high velocity. This implicates that the serratus anterior muscle,
responsible for this movement, lacks power at the dominant, painful shoulder. These results provide the first scientific evidence for impaired protraction force output in overhead athletes with impingement symptoms. Diminished muscle force in the protractors may result in a lack of powerful protraction during the throwing motion\textsuperscript{36}. If the scapula is unable to move in smooth coordination with the humerus during the acceleration phase, this may increase the stresses on the glenohumeral joint and hence jeopardize functional shoulder stability\textsuperscript{61}.

Our study also demonstrated a significant decrease in electromyographic muscle activity in the lower trapezius during an isokinetic retraction movement at high velocity. This decrease may be related to stretch weakness, either postural (chronic protracted shoulder girdle posture) or dynamic (due to mechanical stress during the deceleration phase of throwing)\textsuperscript{33,34,59}. The decreased activity may reflect a muscle imbalance in the trapezius muscle, since side differences in muscle activity were not demonstrated in the middle and upper trapezius, nor were side differences in force output for the retraction movement. The question regarding possible effects of this muscular imbalance on the quality of the retraction movement arises. Insufficient activity of the lower trapezius during retraction may lead to movement deviations of the scapula towards a more elevated position, due to the muscular preponderance of the upper trapezius\textsuperscript{33}. In addition, it has been suggested that lower trapezius activity is necessary to regulate the upward rotation of the scapula\textsuperscript{30}. A lack of such activity could result in more scapular elevation and less upward rotation during retraction. This abnormal scapulothoracic movement pattern recently has been identified as a type III scapular dyskinesia\textsuperscript{38}. This movement impairment potentially places the shoulder in a more vulnerable position with regard to subacromial and internal impingement. However, these assumptions are speculative, and further biomechanical research is mandatory to confirm the association between decreased lower trapezius activity and the quality of scapular retraction movement.
Chapter VI

The quality of the scapulohumeral rhythm primarily depends on the quality of the scapular muscle function, which is provided by several parameters. The absolute and relative timing of trapezius muscle activity, amount of muscle activity of the individual scapular muscles, muscle balance around the scapula, and force output of the scapular protractors and retractors are considered to play a significant role in normal scapulothoracic function\textsuperscript{36,45,53,57,66}. Despite a consensus in the clinical literature, scientific evidence to support this is scarce. The results of this dissertation\textsuperscript{12,13} scientifically confirm these hypotheses\textsuperscript{31,35,36,57} and previous experimental investigations\textsuperscript{16,18,45,58} demonstrating muscle dysfunction in the scapulothoracic joint in overhead athletes with impingement symptoms. Our results add a new dimension to the understanding of impaired neuromuscular control around the scapula in patients with shoulder pathology. Both the trapezius muscle\textsuperscript{12,13} and the serratus anterior\textsuperscript{13} showed alterations in muscle performance in painful shoulders. These findings confirm the hypothesis that an association exists between scapulothoracic dysfunction and glenohumeral impingement.

**Clinical implications and future directions**

The results of the studies presented in this dissertation show that overhead athletes with shoulder pathology demonstrate (1) decreased force output during concentric isokinetic scapulothoracic protraction movements, (2) decreased muscle activity in the lower trapezius during concentric isokinetic retraction movements, and (3) disorders in timing of trapezius muscle activity. These findings raise several questions regarding their clinical implications. The most relevant question in view of designing an appropriate rehabilitation program for the overhead athlete is whether the deficiencies found in our investigations are reversible. In other
In recently published rehabilitation protocols for shoulder pain in overhead athletes, much attention has been paid to the restoration of normal scapulothoracic function. Strengthening of the scapular muscles is often the major treatment goal. The results of our study regarding isokinetic protraction strength confirm previous hypotheses of decreased muscle force in patients with shoulder pain, and hence provide additional arguments for protraction strengthening as a treatment goal in overhead athletes with shoulder pain. Various electromyographic studies have investigated the muscle activity of the scapular muscles during exercises, commonly used in shoulder rehabilitation. Based on the results of these studies, several exercises are promoted to enhance the strength of the scapular muscles. Moseley et al. proposed 6 exercises relevant to increasing muscle activity in the serratus anterior muscle: elevation in the frontal, the sagittal and the scapular plane, the military press movement, and two variants of the push-up movement (Appendix 1). These exercises reflect both functions of the serratus anterior muscle, notably protraction as a linear movement of the scapula on the thoracic wall, and upward rotation of the scapula around a sagittal axis, necessary during functional arm movements. Decker et al. additionally found that exercises that maintained an upwardly rotated scapula while accentuating scapular protraction such as the push-up plus progression (in which a continued scapular protraction is performed after extending the arms in a standard push-up) elicited the highest electromyographic activity from the serratus anterior muscle. In addition, dynamic hug and serratus anterior punch were also found to emphasise serratus anterior activity (Appendix 1).
In summary, numerous exercises have been found to be relevant to serratus anterior training, with the push-up movements being the most important. From a biomechanical point of view, the push-up exercise shows the closest resemblance to the protraction movement, investigated in our studies\textsuperscript{11,13}. Indeed, in our isokinetic protocol, linear protraction-retraction movements were performed, with the elbows extended. Therefore, we think it is important to implement this exercise in the rehabilitation program. The use of the military press exercise should, in our opinion, be avoided in the rehabilitation program, because this shoulder position increases the risk of symptoms in patients with impingement. Moreover, it is generally thought that strengthening exercises in positions which possibly elicit shoulder symptoms should be used with caution\textsuperscript{16}.

In spite of the relevance of scapular protraction exercises, push-up movements exercise only partially the function of the serratus anterior, and do not sufficiently emphasise its upward rotation function\textsuperscript{52}. In addition, this exercise is performed in a closed kinetic chain, whereas the upper extremity often functions in an open kinetic chain. An upward rotation of the scapula is particularly important in throwing movements to elevate the acromion and place the glenoid in an upward-faced position. During the cocking phase the scapula is retracted and rotated, in order to attain the late cocking position\textsuperscript{2}. Therefore, it is imperative to perform open-chain elevation exercises to enhance scapular upward rotation. During these exercises, the quality of the scapulohumeral rhythm should be controlled, and progression should be made rather by implementation of more functional movement components in view of the overhead throwing motion than by increasing the resistance used in the exercise. Future research into the effects of these exercises on the protraction strength in patients with shoulder pain is imperative. In addition, the correlation between an increase in protraction force and functional improvement remains enigmatic and should be studied further.
The results of our study also revealed decreased muscle activity in the lower trapezius during isokinetic retraction. Improvement of this muscle function should thus be focused on in the rehabilitation program. According to Moseley et al., six exercises specifically train the lower trapezius: rowing, two variants of horizontal abduction, scaption (elevation of the arm in the scapular plane), abduction, and forward flexion (Appendix 2). During three of these exercises, the lower trapezius functions as a retractor, and during the other three it rotates the scapula upward. Especially the first exercises show similarities with the movement direction, investigated in our isokinetic evaluation. Therefore, these exercises are extremely relevant to shoulder function, particularly in the overhead athlete, and should, in our opinion, be implemented in the rehabilitation program. The question arises how the contribution of the lower trapezius to the retraction movement can be trained. Indeed, rather than improving muscle strength for the retraction movement, regaining proper muscle balance seems to be the treatment goal. Several attempts have been made to improve lower trapezius activity during scapulothoracic exercises. Facilitatory techniques such as taping, electromyographic biofeedback, or tactile input such as palpation or tapping, have been proposed. These methods have been thought to enhance the isolated conscious muscle control during various exercises. However, research into the effects of these expedients is scarce, and should be intensified to improve our understanding of the underlying mechanisms of these treatment techniques.

It has become clear that muscle force alone is no guarantee for muscle balance and functional joint stability. According to our results, emphasis should be placed on restoring the correct timing of muscle activity among the trapezius parts. Our studies, revealing delayed muscle onset and decreased muscle activity in the lower trapezius provide arguments for this hypothesis. The question, however, arises whether disorders in muscle timing and muscle
balance can be influenced. The most relevant question is how to improve the muscle reaction time of the lower trapezius, and thus re-establish the normal scapular muscle recruitment, and normal muscle activation patterns in the lower extremity-trunk-upper extremity kinetic chain. In the literature no specific exercises have been proposed. Several exercises have been promoted to generally enhance neuromuscular control around the scapula, such as rhythmic stabilisation drills, and closed-chain exercises. According to the authors, these exercises allow the athlete to emphasise on the improvement of neuromuscular control rather than muscle force. Some of these exercises focus on voluntary muscle control of the lower trapezius, others on the reciprocal agonist-antagonist contractions of the scapular muscles under different loads and circumstances. The use of taping and tactile or electromyographic feedback may offer additional assistance in this exercise program where isolated temporal muscle control is the major treatment goal. However, the effectiveness of these exercises on muscle balance and temporal recruitment patterns has not yet been established. Contrary to the scapulothoracic joint, the effect of training on muscle timing has been examined in the knee joint. The results of these studies showed that functional and agility exercises improved this parameter. Similar investigations have not been performed in the shoulder. Future studies should evaluate the effects of several muscular control exercises on muscle balance and temporal recruitment variables in the scapular muscles. Our research has also shown that trapezius muscle reaction times were significantly delayed in the presence of fatigue. Correct timing of the stabilising muscles is, however, important for functional joint stability. In addition, it is often suggested that injuries are frequently related to muscle fatigue. Therefore, we think that endurance training of the trapezius should be implemented in the rehabilitation of scapulothoracic function, as it may increase the resistance of the scapular muscles to fatigue, and possibly avoid slower muscle activation due to fatigue. However, the possible influence of these endurance exercises on muscle latency is
unclear. Future studies should investigate the value of lower trapezius endurance training in the prevention of shoulder pathology in the overhead athlete.

In summary, the results of our studies, showing disturbances in muscle balance and muscle latency, provide arguments for neuromuscular control training of the scapular muscles, often promoted in clinical guidelines for shoulder problems. Further investigations are mandatory to provide a scientific rationale for the use of these exercises.

Literature is not unanimous regarding the cause-consequence relationship between scapulothoracic and glenohumeral dysfunction. According to some authors scapulothoracic dysfunction increases the risk for impingement\textsuperscript{23,33,61,63}. In their opinion the scapulothoracic disorder is a primary problem. Argumentation for this hypothesis is provided by suggesting that the muscle imbalance and muscle recruitment disorders biomechanically lead to a narrowing of the subacromial space or the space between the humeral head and the posterosuperior rim of the glenoid\textsuperscript{5,61}. Others state that scapular muscle inhibition, and resulting scapular instability is a non-specific response to a painful condition at the shoulder\textsuperscript{36,43,57}. These authors suggest that the experience of pain in the glenohumeral joint leads to a secondary inhibition of the scapular muscles, with the serratus anterior and lower trapezius muscles being the most susceptible for this reaction.

Our results do confirm the existence of an association between both problems, but cannot allow us to draw conclusions regarding the primary cause. We can only conclude that scapulothoracic muscle disorders occur in overhead athletes with impingement problems, that these muscle disorders are characterized by a type of muscle inhibition (decreased muscle activity, decreased force output and a delay in muscle onset), and that these disorders mainly are found in the serratus anterior and lower trapezius muscles. In order to further examine the cause-result relationship, a prospective study should be performed on a large group of
healthy, non-symptomatic overhead athletes, measuring several parameters of neuromuscular control. In this kind of investigation, it is possible to investigate a) if an abnormal scapulothoracic function exists in healthy overhead athletes, and b) whether overhead athletes with an abnormal scapulothoracic muscle function are more prone to the development of glenohumeral shoulder problems that overhead athletes with a normal scapulohumeral rhythm. However, in the scope of such a study, normative data are needed regarding the variables examined in our project. Contrary to neuromuscular performance data of the glenohumeral joint, these normative data from healthy overhead athletes are still unknown, as well for the muscle latency times as for the isokinetic force values. Future studies should emphasise the development of a normative database for scapular muscle function for several sport disciplines, and different age categories.

Since the rehabilitation of the scapulothoracic function should be integrated into the global shoulder rehabilitation program for the overhead athlete with impingement symptoms, the sequence of both aspects, glenohumeral and scapulothoracic training, should be discussed. Although the literature is not unanimous regarding the cause-consequence relationship between scapulothoracic and glenohumeral dysfunction, there is a general agreement that the restoration of scapulothoracic muscle function should precede functional glenohumeral training. Indeed, the scapula functions as a stable proximal base for the glenohumeral joint in all shoulder positions and movements. In addition, the scapular muscles are considered to be a very important link in the kinetic chain, transferring energy from the legs and the trunk to the throwing shoulder. In view of this consideration, muscle training of the distal glenohumeral muscles should be progressively integrated in the treatment protocol, after proper rehabilitation of muscle control of the proximal links in the chain.
Final conclusions

The key to successful rehabilitation is a thorough and systematic evaluation of the glenohumeral and scapulothoracic function to establish aberrant neuromuscular control and to identify specific muscle imbalances. Not only should muscle force be examined, but also muscle control, balance and muscle timing properties. This doctoral dissertation deals with some of these variables of neuromuscular control. In the overhead athlete, inadequate dynamic scapulothoracic stability frequently produces functional instability, resulting in shoulder dysfunction and pain. Isokinetic muscle performance of the scapular muscles, muscle balance within the trapezius, and timing of muscle activity of the trapezius were examined in this dissertation, and to some extent found to be disturbed in overhead athletes with impingement symptoms and functional shoulder instability.

The evaluation and rehabilitation of the scapulothoracic function is challenging and exciting. New concepts in basic and clinical sciences are being explored to improve the evaluation and treatment of overhead athletes with shoulder pain. The aim of this doctoral dissertation is to improve the understanding of scapulothoracic function in normal and painful shoulders. The continued integration and development of new knowledge provide further insights into current concepts in shoulder rehabilitation.
REFERENCES


CHAPTER VII

NEDERLANDSE SAMENVATTING
Chronische schouderklachten komen frequent voor bij atleten die een bovenhandse sport beoefenen. Tijdens de bovenhandse slag-, werp-, of zwembeweging wordt de schouder immers aan extreem hoge belastingen onderworpen, die de integriteit van de capsuloligamentaire structuren en de stabiliteit van het gewricht in gevaar brengen. Schouderinstabiliteit en impingement zijn frequent voorkomende oorzaken van schouderklachten bij bovenhandse atleten.

De schouder heeft omwille van zijn aanzienlijke mobiliteit een groot deel van zijn structurele stabiliteit moeten prijsgeven. Dit gewricht wordt dan ook vaak als “inherent instabiel” beschouwd. Door het gebrek aan mechanische stijfheid moet het in grote mate beroep doen op een optimale spierfunctie om de functionele stabiliteit te garanderen.

Een belangrijke rol in deze functionele schouderstabiliteit is weggelegd voor de scapula. Het schouderblad fungeert immers als stabiele basis voor het glenohumeraal gewricht. Bovendien is de scapula een aanhechtingspunt voor zowel axioscapulaire als glenohumerale spieren, en is het een belangrijke schakel in de kinetische keten die tijdens bovenhandse bewegingen de noodzakelijke energie moet overbrengen van de romp naar de werpende hand. De scapulaire stabiliteit en mobiliteit hangt in grote mate af van de coördinatie van de verschillende scapulothoracale spieren. De trapezius en de serratus anterior worden beschouwd als de belangrijkste scapulaire stabilisatoren.

Reeds geruime tijd vermoedt men dat er een verband bestaat tussen glenohumerale klachten en een disfunctie in het scapulothoracaal gewricht. In de literatuur wordt vaak gesuggereerd dat patiënten met impingement klachten en functionele instabiliteit afwijkingen zouden vertonen in het bewegingspatroon van de scapula, en in de spieractiviteit van de scapulaire spieren. Vooral de serratus anterior en de trapezius pars ascendens zouden minder actief zijn.
in deze populatie. Verscheidene studies hebben reeds aangetoond dat patiënten met schouderklachten afwijkingen vertonen in het scapulohumeraal ritme, en minder electromyografische activiteit genereren in de scapulaire spieren.

Een optimaal musculair evenwicht in het scapulothoracaal gewricht is echter niet enkel afhankelijk van de intensiteit van de spieractiviteit in de scapulothoracale spieren. Ook de timing van de spieractivatie en de onderlinge spierrekruteringsvolgorde worden als belangrijke parameters beschouwd van het musculaire evenwicht. Dit aspect van de neuromusculaire coördinatie is echter tot nog toe niet onderzocht in het scapulothoracaal gewricht. Daarom werd in een eerste studie het scapulothoracaal spierrekruteringspatroon geëvalueerd bij een gezonde populatie. De resultaten van deze studie tonen aan dat in een gezonde schouder, bij een onverwachte valbeweging van de arm, de drie trapeziusbundels tegelijk geactiveerd worden om het evenwicht te herstellen. In dit onderzoek werd ook nagegaan welke de effecten zijn van vermoeidheid op de spierlatentietijden. Dit gegeven is klinisch relevant aangezien schouderklachten vaak gerelateerd worden aan het optreden van musculaire vermoeidheid. De resultaten tonen aan dat bij vermoeidheid de spierreactietijden vertraagd zijn, maar de rekruteringsvolgorde ongewijzigd blijft.

In een tweede onderzoek werden de spierlatentietijden geëvalueerd bij bovenhandse atleten met schouderklachten. Uit deze studie blijkt dat bij de patiënten de spierlatentietijden langer zijn dan bij een controlegroep, en dat deze vertraagde reactie zich vooral manifesteert in de trapezius pars ascendens. Bovendien komen de afwijkingen in de spierlatentietijden bilateraal voor. Uit deze studie kan geconcludeerd worden dat er een stoornis is in de spierrekruterings van de trapezius bij patiënten met impingement en functionele instabiliëteit, waarbij voornamelijk disfuncties terug te vinden zijn in de timing van de onderste trapeziusbundel.

Naast de evaluatie van electromyografische spieractiviteit, is de isokinetische krachtevaluatie van grote waarde in het objectief onderzoek naar de scapulothoracale spierfunctie. In
tegenstelling tot de andere gewrichten werd tot nog toe de isokinetische kracht tijdens schoudergordel protractie en -retractie niet objectief wetenschappelijk geëvalueerd. Daarom werd in een derde studie de reproduceerbaarheid van dit nieuwe isokinetische protocol getest. Uit de resultaten blijkt dat de isokinetische krachtevaluatie van de scapulaire protractie en retractiebewegingen zeer betrouwbaar is.

In een laatste studie werd de isokinetische protractie en -retractiekracht geëvalueerd bij bovenhandse sporters met impingement symptomen. Simultaan werd de electromyografische spieractiviteit geregistreerd in de scapulaire spieren. De resultaten van deze studie tonen aan dat aan de pijnlijke zijde, de patiënten een verminderde protractiekracht hebben. Dit zou kunnen wijzen op krachtsvermindering in de serratus anterior, en aldus vroeger geformuleerde hypotheses met betrekking tot inhibitie van deze spiergroep bevestigen. Uit het electromyografisch onderzoek blijkt bovendien dat tijdens isokinetische retractie, er een verminderde spieractiviteit is in de trapezius pars ascendens. Dit betekent dat er mogelijks een musculair onevenwicht is binnen de trapeziusbundels.

De vraag dringt zich op welke de klinische implicaties zijn van onze onderzoeksresultaten. In de klinische literatuur wordt vaak aangeraden om scapulothoracale spiertraining te incorporeren in de revalidatie van de pijnlijke schouder bij de atleet. Onze resultaten bevestigen het belang van het trainen van de serratus anterior en het herstellen van het musculair evenwicht in de trapezius met speciale aandacht voor de correcte timing van spieractivatie van deze spierbundel. Bovendien is het verbeteren van de uithouding om aldus vermoeidheid in de scapulaire spieren te minimaliseren van groot belang.

Een systematische evaluatie van de glenohumerale en scapulothoracale spierfunctie is de sleutel tot een succesvolle revalidatie van de bovenhandse atleet met schouderklachten. Daarin moeten zowel de kracht, als de musculaire controle, het musculaire evenwicht, de individuele spieractiviteit, de spierlatentietijd en het spierrekruteringspatroon aan bod komen.
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Dit proefschrift behandelt verschillende van deze aspecten en wil op deze manier een wetenschappelijke en klinisch bijdrage bieden aan de evaluatie en revalidatie van de atleet met schouderklachten.
APPENDIX 1: Rehabilitation exercises for serratus anterior training

Exercise 1: Abduction – Elevation in the frontal plane
Description: the subject starts with his arm in neutral position and elevates his arm in the frontal plane, until full range of motion.

Exercise 2: Forward flexion – Elevation in the sagittal plane
Description: the subject starts with his arm in neutral position and elevates his arm in the sagittal plane, until full range of motion.
Exercise 3: Scaption – Elevation in the scapular plane

Description: the subject starts with his arm in neutral position and elevates his arm in the scapular plane (30-45° anterior of the frontal plane), until full range of motion.

Exercise 5: Push up with a plus

Description: subject performs a push-up movement on the floor or against the wall, with an additional protraction movement of the scapulae at the end of the movement.
**Exercise 6: Push up with the hands apart**

Description: subjects performs a push up movement on the floor or against the wall, with the hands wide apart.

![Push up with hands apart](image1)

**Exercise 7: Dynamic hug**

Description: the subject is standing with the elbows flexed 45°, the arm abducted 60°, and the shoulder internally rotated 45°. He performs a horizontal flexion movement against an elastic resistance by following an arc described by his hands (hugging action).

![Dynamic hug](image2)
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Exercise 8: Serratus anterior punch

Description: the subject is standing, and the handle of the elastic resistance is grasped at shoulder height with the elbow extended, the humerus internally rotated 45°, and the scapula in retraction. The subject performs a protraction movement against the resistance, keeping the elbow extended.
APPENDIX 2: Rehabilitation exercises for lower trapezius training

Exercise 1: abduction – elevation in the frontal plane
Description: the subject starts with his arm in neutral position and elevates his arm in the frontal plane, until full range of motion. (Appendix 1, Exercise 1)

Exercise 2: forward flexion – elevation in the sagittal plane
Description: the subject starts with his arm in neutral position and elevates his arm in the sagittal plane, until full range of motion. (Appendix 1, exercise 2)

Exercise 3: Scaption – elevation in the scapular plane
Description: the subject starts with his arm in neutral position and elevates his arm in the scapular plane (30-45° anterior of the frontal plane), until full range of motion. (Appendix 1, Exercise 3)

Exercise 4: Rowing
Description: the subjects starts with his arms flexed in the sagittal plane 90°, elbows extended, and pulls his arms backwards with the elbows flexed, keeping arms close to the body. Dumbbells as well as elastic resistance can be used.
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Exercise 5: Horizontal abduction in neutral rotation

Description: the subjects starts with his arms flexed in the sagittal plane 90°, elbows extended, and performs a horizontal abduction until 90° of abduction. Dumbbells as well as elastic resistance can be used.
Exercise 6: Horizontal abduction with external rotation

Description: the subject starts with his arms flexed in the sagittal plane 90°, elbows extended, and performs a horizontal abduction until 90° of abduction, with an additional external rotation of the humerus (“thumbs up at the end of the movement”). Dumbbells as well as elastic resistance can be used.
ABSTRACT.

Overhead athletes often develop shoulder pain as a result of repetitive overstress on their shoulder structures. Impingement symptoms are the most frequent shoulder complaints in athletes performing overhead sports such as tennis or volley ball. Optimal shoulder function depends among others on the smooth coordination between glenohumeral and scapulothoracic movement patterns. It has been hypothesised that overhead athletes with shoulder problems show deficiencies in the neuromuscular performance of the scapulothoracic joint. The purpose of this thesis was to evaluate muscle force, muscle balance and timing of muscle activity in the scapular muscles in a patient group consisting of overhead athletes with shoulder impingement and to compare their results with a healthy control group.

In a first study line, the timing of muscle activity of the trapezius muscle was evaluated in response to a sudden movement of the arm. It was found that in the patient group, there was a significant delay in the lower trapezius muscle and a significant lack of coordination between the different trapezius muscle parts.

In a second study line, isokinetic muscle force was measured during a scapular protraction-retraction movement in the scapular plane, with simultaneous recording of the EMG activity in the scapular muscles. The results of these studies showed that overhead athletes with shoulder pain show a significant decrease in force output of the serratus anterior during a protraction movement at high velocity, and a significant muscle imbalance with a lack of activity in the lower trapezius during isokinetic retraction movements.

This thesis confirms the hypothesis that overhead athletes with shoulder impingement have muscle dysfunction at the scapulothoracic joint. These results may have clinical implications
in the prevention and rehabilitation of shoulder pain in overhead athletes and thus may improve the functional performance in their sports.