Electromyographic Assessment of Muscle Fatigue in Massive Rotator Cuff Tear

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Introduction

Effective shoulder function is essential for many activities of daily living. Coordinated synchronous activity of shoulder girdle muscles is required to limit translation of the humeral head on the shallow glenoid fossa [Bey et al., 2008; Poppen et al., 1978]. Rotator cuff muscle activity plays a fundamental role in maintaining glenohumeral joint (GHJ) stability[Burkhart, 1991; Inman et al., 1996; Yanagawa et al., 2008], 'stiffening' the GHJ to establish a stable fulcrum[David et al., 2000].

Rotator cuff tears are prevalent in the elderly[Sher et al., 1995; Tempelhof et al., 1999]. A tear larger than 5 cm or involving 2 or more rotator cuff tendons is defined as a 'massive rotator cuff tear' (MRCT). [Cofield, 1981; Gerber et al., 2000]. An MRCT often has significant impact on quality of life due to impaired shoulder strength and range of movement, and consequently reduced ability to perform essential daily activities. MRCT disrupts the glenohumeral fulcrum, leading to abnormal superior translation of the humeral head on the glenoid fossa during arm elevation as the destabilising force generated by the deltoid muscle is unopposed[Terrier et al., 2007; Yamaguchi et al., 2000]. The altered joint mechanics results in a disabling condition which can impact on functional capacity and quality of life. However, despite this anatomical deficit, some patients with a MRCT are able to maintain function. This has led to the hypothesis that alternative muscle activation strategies can compensate for the deficient rotator cuff to establish a stable glenohumeral fulcrum for arm movement[Hansen et al., 2008; Steenbrink et al., 2006; Steenbrink et al., 2009].

The outcome of surgical interventions for MRCT depends on several factors such as age, activity level, joint stability, and associated degenerative changes.[Dines et al., 2006; Gerber et al., 2011] High rates of re-tear follow rotator cuff repair[Galatz et al., 2004] and tendon transfer or shoulder arthroplasty are the main options when the tear is irreparable[Boes et al., 2006]. Physiotherapy has been suggested as a key alternative intervention in the management of MRCT when surgery is not feasible. [Ainsworth et al., 2007]. However, evidence is lacking to support the development of effective rehabilitation protocols which target compensatory muscle activation strategies and fatigue-susceptible muscles. While a few studies have investigated the activation pattern of shoulder girdle muscles in MRCT, their fatigability not been studied. Identification of potentially fatigable muscles in the upper limb kinetic chain is needed to support the development of tailored rehabilitation protocols.

Muscular fatigue is a time-dependent process occurring during muscular contraction, resulting in manifestations such as tremor, pain and inability to achieve a desired force output[De Luca, 1984]. Its importance in MRCT is that altered muscle force generation caused by deficient rotator cuff function may contribute to decreased GHJ stability. Shoulder muscle fatigue has been studied using electromyography (EMG) in healthy subjects during isometric arm elevation tasks, in which the greatest fatigue is observed in the deltoid and rotator cuff muscles[Minning et al., 2007; Nieminen et al., 1995]. However, appropriate measurement of muscle fatigue in painful conditions such as MRCT presents a significant challenge.

Shoulder pain directly alters muscle activation strategies, partly to protect painful structures[Diederichsen et al., 2009] and partly as movement avoidance due to fear of pain [Alizadehkhaiyat et al., 2007]. These factors complicate comparisons with healthy controls, so an alternative approach is required. Hand grip tasks activate key shoulder girdle muscles by exploiting the principles of the kinetic chain[Alizadehkhaiyat et al., 2011; Sporrong et al., 1995; 1996; Sporrong et al., 1998]. This can provide a practical way of studying shoulder muscle fatigue, albeit only in a particular position, in patients with MRCT while limiting pain and potential sources of confounding.

Shoulder muscle fatigue has not been measured before in MRCT. Hence, the central aim of the present study was to determine and compare the fatigability of key shoulder girdle muscles in groups of MRCT patients and healthy controls during a pain-free task representative of daily activities. We further aimed to evaluate the functional impact of MRCT on patients' quality of life using validated scores. The combined results are intended to provide a base of knowledge for future clinical studies aiming to compare current rehabilitation protocols and promote the development of effective evidence-based programmes.

Methods

Participants

The control group (CG) comprised 14 healthy subjects with no history of upper limb painful conditions or surgery, and normal upper limb clinical examination. The mean (± SD) age was 36±15 y, height 175±10 cm and mass 77±15 kg. The arm tested was randomly selected. The MRCT group (MRCTG) including 12 patients were recruited from a specialised Upper Limb Unit in a major orthopaedic centre during 2009-2011. All patients presented with a painful shoulder and had positive clinical tests (including lag signs) for MRCT. Considering that clinical diagnosis of a MRCT cannot be conclusively reached using one or more of the clinical signs[Miller et al., 2008], the presence of MRCT was later confirmed by ultrasound or magnetic resonance imaging. Patients had no coexisting musculoskeletal disorder affecting the upper limb. Mean age was 74±7 y, height 166±8 cm, and weight 78±14 kg. Six patients had a tear of supraspinatus and infraspinatus, 5 of supraspinatus, infraspinatus and subscapularis, and 1 of supraspinatus and subscapularis. The study had Local Research Ethics Committee approval and written informed consent was obtained from all participants.

Repeatability was assessed by re-testing 4 subjects from CG 2-8 weeks after their first visit. Study groups were the same as those reported in an earlier study of muscle activation and coordination in MRCT[Hawkes et al., 2011].

EMG Measurement

EMG was recorded from 13 shoulder muscles during the hand grip protocol described below. A TeleMyo 2400 G2 Telemetry System (Noraxon Inc., Arizona, USA) was used for signal acquisition. Recorded signals were analysed off-line using MyoResearch XP software (Noraxon Inc., Arizona, USA). Signals were differentially amplified (common mode rejection ratio >100dB; input impedance >100Mohm; gain 500dB), digitised at a sampling rate of 3000Hz and band-pass filtered in accordance with international guidance ([10-500]Hz for surface electrodes and [10-1500]Hz for fine wire electrodes)[ISEK, 1996]. ECG contamination was removed from affected signals using an adaptive cancellation algorithm.

Disposable, self-adhesive pre-gelled Ag/AgCl bipolar electrodes with conducting area of 10mm diameter and inter-electrode distance of 20mm (Noraxon Inc., Arizon, USA) were used to record the EMG from anterior, middle, and posterior deltoid (AD, MD, PD), pectoralis major (PM), upper trapezius (UT), serratus anterior (SA), latissimus dorsi (LD), teres major (TM), brachioradialis (BR) and biceps brachii (BB) according to guidelines [Caldwell et al., 1993; Gartsman, 1997; Kadaba et al., 1992; SENIAM]. Skin preparation involved shaving and application of abrasive paste (Nuprep, Weaver and Company, Aurora, USA). Crosstalk was limited by the judicious placement of appropriately sized electrodes, parallel to the muscle fibres and according to accepted anatomical criteria[Basmajian et al., 1985]. Fine wire electrodes were used to record signals from the supraspinatus (SSP), infraspinatus (ISP) and subscapularis (SUBS). Bipolar disposable hook wire electrodes (Nicolet Biomedical, Division of VIASYS, Madison, USA) were inserted aseptically using the accepted technique[Basmajian et al., 1985]. Signals were reviewed and excluded if of low signal-to-noise ratio or if manual muscle testing indicated incorrect electrode placement.

Hand Grip Testing Protocol

Grip strength was measured using a Jamar dynamometer (Biometrics Ltd., E-LINK, Gwent, UK). Subjects were tested seated on a chair with their hips and knees flexed to 90^o; wrist and forearm in neutral position, elbow extended to 180^o, and the shoulder in neutral rotation and elevated to 30^o in the scapular plane (Figure 1). A goniometer ensured the correct angle of arm elevation and a guidance pole was positioned to maintain the testing position. Subjects were instructed to squeeze the dynamometer maximally (build gradually to the maximal exertion) during a 3-second trial. Three trials were performed and the average was taken as maximum voluntary contraction (MVC)[Mathiowetz et al., 1984]. Verbal encouragement was provided, participants being encouraged to exceed each previous measurement[Baratta et al., 1998].

An isometric task is considered most appropriate for studying muscle fatigue[Merletti et al., 1991; Viitasalo et al., 1975]. Typically, shoulder fatigue is studied in isometric contraction at a predefined fraction of the MVC. This approach will not work where pain significantly affects measurement of true MVC: all that can be determined is the 'acceptable maximal effort', which can show marked day-to-day variability[Graven-Nielsen et al., 2002]. Comparisons with normal controls can also be undermined by fear-related movement avoidance and pain-related alterations in muscle activation[Alizadehkhaiyat et al., 2007; Diederichsen et al., 2009]. Thus fatiguing EMG signals were recorded during sustained submaximal hand grip at 25% MVC ($MVC_{25\%}$) of absolute strength differences in a testing position (see above) which minimises interference from pain in the shoulder girdle muscles.

Visual feedback was provided and subjects exerted a constant grip force for about 60 seconds, or until exhaustion point defined as a sustained (> 5s) drop of > 5% in grip force.

Changes in the median frequency (MDF) of the EMG signal were taken as an indirect measure of fatigue. MDF is less susceptible to noise than the mean frequency and has been commonly used to quantify muscle fatigue [Hof, 1991; Stulen et al., 1981]. EMG amplitude often shows inconsistent changes in fatiguing contractions, and has fallen out of favour as a fatigue index [Dimitrova et al., 2003; Vollestad, 1997].

Patient Self-Reported Questionnaires

All subjects completed the questionnaires prior to EMG assessment including the Oxford Shoulder Score (OSS)[Dawson et al., 2009] and the Upper Limb Functional Index[Gabel et al., 2006]. These provide reliable and valid assessment of functional status and health-related quality of life in painful shoulder conditions; the OSS in particular has been used widely, typically to assess outcomes of surgery[Hanusch et al., 2009; Olley et al., 2008]. The OSS is scored 0-48 (0 = worst function) and the ULFI is scored 0-100% (100% = worst function).

Data Management and Statistical Analysis

The first and last 5-s EMG recordings were excluded from the analysis. Fast Fourier Transformation was performed to allow analysis of the power spectrum. MDF was calculated in 1s epochs which were normalised relative to the start value. The mean rate of change of MDF during the contraction (assessed by linear regression) was used as the fatigue index: a regression t-test determined whether this slope differed significantly from zero, a significant p-value indicating EMG evidence of fatigue.

Results are expressed as mean ± standard deviation (SD) or standard error of the mean (SEM) as appropriate. The independent samples *t*-test compared differences between the study groups; a $p < 0.05$ was accepted as significant. Repeatability was assessed using the paired samples t-test to compare test–retest data.

Results

All subjects completed the study protocol, with no dropout due to pain or other factors. There were no significant intra-session effects with regard to the normalised MDF slope or initial MDF for any of the muscles studied.

Range of Movement

The mean range of movement for flexion, abduction and external rotation in the affected shoulder of the MRCTG was 97±46, 83±47, and 39±11, respectively. All measurements were significantly lower than those in the CG ($p = 0.001$).

Grip Strength

Individual maximum grip strength ($MVC_{100\%}$) was used to calculate the submaximal voluntary contraction ($MVC_{25\%}$) applied during the fatigue testing protocol. Mean $MVC_{100\%}$ was 24±12 kg and 43±14 kg for MRCTG and CG, respectively ($p = 0.001$).

EMG

Table 1 presents the time-course of MDF for the studied muscles. The fatigue index (MDF slope%/min) was significantly non-zero (negative) for the AD, MD, PD, BR, SSP and SUBS muscles in the CG and for the AD, MD, PD, PM and BR muscles in the MRCTG. Fatigue was significantly greater in the MRCTG compared to the CG, for the AD, MD and PM (Figure 2) muscles. The higher initial MDF in the SSP, ISP and SUBS reflects the use of fine wire electrodes: signals are detected before they pass through the skin and subcutaneous tissue which has a low pass filtering effect[Basmajian et al., 1985].

Patient Self-Reported Questionnaires

The results of self-reported questionnaires indicated significantly worse functional capacity and health-related quality of life in the MRCTG compared to the CG (ULFI: 36 ± 25 vs. 0; and OSS: 47±1 vs. 29±10) (p = 0.001).

Discussion

Peripheral (muscular)[Merton, 1954] and central (central nervous system)[Brasil-Neto et al., 1994; Brasil-Neto et al., 1993] factors contribute to localised muscular fatigue according to the particular demands of the motor task. EMG has been extensively used to study muscular fatigue, and its consistent lower-frequency shift during sustained contraction underlies the application of the MDF slope as a fatigue index [Hof, 1991; Stulen et al., 1981].

Fatigue has been little studied in normal shoulders using EMG. Minning et al. studied 16 healthy subjects during an isometric contraction at 90^o in the scapular plane at 60% MVC and concluded that fatigue was greater in the MD than in the upper and lower trapezius and SA muscles[Minning et al., 2007]. Nieminen et al. studied 10 healthy subjects during an isometric flexion task at 90^o of humeral elevation and reported that deltoid, ISP and SSP were the first to show signs of fatigue[Nieminen et al., 1995]. There has been no previous work on fatigue in MRCT.

Grip strength correlates strongly with health-related quality of life and is a powerful predictor of disability, morbidity and mortality[Bohannon, 2008; Sayer et al., 2006; Syddall et al., 2003]. As well as finger flexors, forceful grip activates finger extensors to stabilise the wrist[Alizadehkhaiyat et al., 2008; Hagg et al., 1997]. The kinetic chain principle that activation of proximal muscle groups ensures stability within distal segments is particularly pertinent to the GHJ, where muscular activity plays a key role in maintaining joint stability[Hawkes et al.]. The activation of shoulder muscles during hand grip tasks has been previously demonstrated in healthy subjects [Alizadehkhaiyat et al., 2011][Sporrong et al., 1995; Sporrong et al., 1998]. Here we found reliable EMG evidence of fatigue in the AD, MD, PD, BR, SSP and SUBS muscles of the CG using a simple protocol that all patients were able to complete without interference by pain. We therefore believe that this grip protocol provides a useful, valid way to study muscle fatigue in painful shoulder conditions.

Despite a significant diffrence in the grip strength between patient and control groups, this is not expected to have affected the results as EMG recording was performed at an equal fraction of achievable maximal contraction (25%) in each group. Thus both groups applied a similar degree of grip exertion, which would be expected to activate the shoulder muscles to approximately the same relative extent. Significant fatigue progression was seen in the AD, MD and PD muscles in both study groups. The testing protocol incorporated 30^o of elevation in the scapular plane; this represents a functional plane of shoulder movement[Johnson et al., 2001] and a hand grip task in this position was considered to reflect many everyday activities, and fatigue was anticipated particularly in the deltoid, a primary elevator of the upper limb[Liu et al., 1997].

Significantly greater fatigue was identified in the AD and MD in the MRCTG. This difference is unlikely to be age-related, as there is evidence that older individuals develop less muscle fatigue than young individuals during maximal and submaximal isometric contractions. Furthermore, age-related changes in muscle morphology and motor units as well as loss of strength and slowed contractile properties are associated with improved resistance to neuromuscular fatigue in older age[Allman et al,. 2002; Christie et al., 2011; Avin et al., 2011]. As torn SSP can no longer develop abduction torque at the GHJ, an additional compensatory work load may be imposed on the deltoid during arm elevation.

Greater fatigue in the AD and MD muscles in the MRCTG may reflect this compensatory role.

This finding is consistent with indirect evidence from other studies. Hansen et al, utilising a cadaveric shoulder model, concluded that for 6-8cm rotator cuff tears a 22-45% increase in deltoid force was necessary to elevate the arm[Hansen et al., 2008]. McCully et al. demonstrated increased deltoid activity in patients with rotator cuff dysfunction modelled experimentally by a suprascapular nerve block[McCully et al., 2006]. This is the rationale for MRCT rehabilitation protocols that target the deltoid[Ainsworth]. However, this only represents half the challenge for MRCT patients.

In normal shoulders, the rotator cuff has an important role in limiting humeral head migration and maintaining GHJ stability. Indeed, significant fatigue progression was seen in the SSP and SUBS in the CG, and there was a trend towards fatigue progression in the ISP. Superior migration of the humeral head, in response to the increased and unbalanced contraction of the deltoid, is characteristic of MRCT[Terrier et al., 2007; Yamaguchi et al., 2000] which leads to the narrowing of the subacromial space and disruption of the glenohumeral fulcrum.

Patients with a MRCT must counter the superior subluxing force of the deltoid during arm elevation and establish a stable GHJ fulcrum for arm movement. Increased activity of the deltoid, which compensates for the lost supraspinatus abduction torque, paradoxically exacerbates the problem. Interestingly, no significant fatigue was seen in the rotator cuff muscles in the MRCTG, perhaps because these muscles cannot develop appreciable force as they are contracting against a torn tendon.

MRCT patients must adopt alternative strategies to balance the increased subluxing force of the deltoid. According to the concept of ‘adductor muscle co-contraction’ during arm elevation[Steenbrink et al., 2006; Steenbrink et al., 2009], contraction of muscles with a line of pull that opposes the superior subluxing force of deltoid can balance the destabilising forces and result in a stable GHJ fulcrum. EMG and computer simulation programmes have identified compensatory roles for LD, TM and PM[Hawkes et al., 2011; Steenbrink et al., 2006; Steenbrink et al., 2009]. Referring to these muscles as ‘adductors’, can obscure appreciation of their essential role in supporting stability during other shoulder movements. In the present study, progression of fatigue in PM was significantly higher in the MRCTG compared to CG. The PM can generate an adduction torque at the GHJ and thus stabilise the humeral head against the superior subluxing force of the deltoid[Paton et al., 1994]. Increased PM fatigue in the MRCTG might reflect this compensatory strategy.

Despite the compensatory role previously advocated for LD and TM[Hawkes et al., 2011; Steenbrink et al., 2006], they showed no significant fatigue progression in this study. Inconsistent changes in MDF have previously been seen during low intensity contractions owing to alternating motor unit recruitment[Farina et al., 2006], reflecting force distribution within muscular compartments[Sjogaard et al., 2004]. Newly recruited motor units will contribute to the power spectrum in either the high or low frequency bands depending on their conduction velocity and location within the muscle[Farina et al., 2003]. It is possible that the low intensity contraction employed in our testing protocol protected the LD and TM against detectable fatigue progression. Furthermore, it is likely that adaptive strategies will change according to the nature of the motor task undertaken.

Patient-rated scores have become an important way of evaluating the impact of diseases on health-related quality of life and the outcome of applied interventions. Functional impact and quality of life are directly relevant to patients and so should form part of clinical assessment[MacDermid et al., 2004]. In this study significant differences were identified between the study groups with regard to the OSS and ULFI. This illustrates the functional deficit in the MRCTG and the negative impact tears have on functional status and quality of life. The mean OSS in the MRCTG was 29; this is consistent with a study by Ainsworth of 10 MRCT patients with a mean OSS of 26[Ainsworth, 2006]. While an age-related bias has been reported for some shoulder measures such as Constant-Murley score[Romeo et al., 1999], it has not been the case for the majority of shoulder scoring instruments including OSS.[Brinker et al., 2002; Mok et al., 2012] Furthermore, shoulder scores using only the patient's subjective report prevent clinical measurements or clinician input to influence the score.[Brinker et al., 2002; Masten et al., 1995; Mok et al., 2012] Hence, it is unlikely that results reported here were affected by instrument bias.

The limitations of this study are acknowledged. There was a age difference between the study groups. However, the study aimed to explore fatigue progression rather than absolute strength differences between the groups; the fatiguing contraction was normalised to $MVC_{25\%}$ and this should minimise the impact of this strength differences. While hand grip provides a good method for the pain-free assessment of fatigue in the shoulder muscles, it has to be remembered that muscular fatigue is task-dependent, and so the results cannot necessarily be generalised to other movements. Furthermore, it is likely that low intensity contraction used for EMG recording protected the larger muscles from fatigue. Hence, incorporating different tasks at varying intensities would extend our understanding. Finally, the heterogeneity of the tear patterns in the MRCTG makes sub-group analysis difficult; stratification by tear pattern would facilitate a better understanding of tear specific adaptive strategies.

Muscular fatigue has not been previously considered in MRCT patients and this study addresses an important gap in the literature. Physiotherapy has an important role in the non-surgical management of these patients. Rehabilitation protocols need to be both evidence-based and targeted. The lack of high quality studies evaluating the role of physiotherapy illustrates an incomplete understanding of the strategies necessary to retain good shoulder function in MRCT. The present results suggest that deltoid rehabilitation might be beneficial in MRCT patients by assisting in compensating for the lost SST abduction torque. In this case, concurrent rehabilitation of muscles functioning to balance the superior subluxing forces on the humeral head will be advantageous. The PM can exert an inferiorly stabilising force on the humeral head, and the results of this study support an important compensatory role. Clinical trials will be required to test these ideas. Effective compensatory strategies are likely to be dynamic and differ based on task-specific demands; this should be taking explicitly into account in the development of rehabilitation protocols.

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TABLE LEGENDS

Table1. Median frequency (MDF): initial values (Hz) and MDF slope (%/min) for the studied muscles in controls and patient groups.

FIGURE CAPTIONS

Figure1: Protocol set-up for EMG recording.

Figure2. Normalised MDF for PM during contraction in the Controls (solid line) and MRCT patients (dashed line).