**Can grip strength be used as a surrogate marker to monitor recovery from shoulder fatigue?**

David Hawkes1, Michael Grant2, Jessica McMahon3, Ian Horsley4, Omid Khaiyat3

1 Musculoskeletal Science Research Group, Institute of Translational Medicine, University of Liverpool, Liverpool, UK

2 Specialty Registrar, Trauma and Orthopaedic Surgery, North West (Mersey) Deanery, Liverpool, UK

3 School of Health Sciences, Liverpool Hope University, Liverpool, UK

4 England Institute for Sport, Sports City, Manchester, UK

*Corresponding Author*: David H Hawkes

*Email*: daveh\_11@yahoo.co.uk

*Address*: Musculoskeletal Science Research Group, Institute of Translational Medicine, University of Liverpool, Liverpool, UK

*Phone*: +44 (0)151 706 4120; *Fax*: +44 (0) 151 706 5826

**Funding**: No funding was received for this work

**Conflict of Interests**: There are no conflicts to declare

**Key Words**: Grip strength; shoulder fatigue; injury prevention; return to play

**ABSTRACT**

Muscular fatigue impacts on normal shoulder function, which is particularly pertinent to throwing athletes. This study aimed to investigate the relationship between grip strength and shoulder muscle fatigue to evaluate the role of grip strength as a surrogate measure for upper limb performance. Twenty healthy participants were recruited. EMG was recorded from 15 shoulder muscles during different fatiguing contractions: an initial baseline recording (Fat-Baseline); after a shoulder exhausting exercise regime (Fat-Exhaustion); and after a 10 minute rest period (Fat-Recovery). Grip strength was similarly measured in the same conditions. Grip strength differed significantly across the testing scenarios (p= 0.012 - <0.001). Greater fatigue was seen in anterior deltoid, middle deltoid, posterior deltoid and supraspinatus in the Fat-Exhaustion contraction as compared to the Fat-Baseline contraction (p=<0.001-0.043). Greater fatigue was seen during the Fat-Recovery contraction for the trapezius, serratus anterior and biceps brachii as compared to the Fat-Exhaustion contraction (p=0.008-0.038). Grip strength decreased following an exhausting exercise protocol but recovered to baseline following a rest period. Conversely, EMG indices of fatigue did not recover. Additional fatigue was seen reflecting a reorganisation of movement strategy. Therefore, susceptibility to injury still exists if grip strength alone is used as a barometer of upper limb performance.

**1. INTRODUCTION**

The shoulder, owing to its limited osseous congruity, relies heavily on coordinated muscle activity for normal function [Lugo et al., 2008]. Muscular endurance is an important component, especially during sustained tasks. Muscular fatigue, a time dependant process, occurs from the onset of a muscular contraction and is associated with external manifestations such as muscular tremor and pain. Fatigue differs from the failure point, the latter being the time at which a desired force output can no longer be maintained [De Luca, 1984].

Electromyography (EMG) is an accepted method of studying fatigue. EMG-driven indices of fatigue show a time-dependant change over the duration of muscular contraction, with a shift of the power spectrum towards lower frequencies [Dimitrova et al., 2003, Hagg, 1992, Merletti et al., 1991]. EMG has been used extensively to study shoulder muscle fatigue in both healthy subjects and patients with pathology. Weak and fatigue-susceptible muscles influence shoulder function by disrupting the normally balanced force couples [Bradley et al., 1991, Glousman, 1993, Gowan et al., 1987]. Adaptations in movement strategy occur in an attempt to maintain performance level, whilst protecting the fatigued [Andrade et al., 2016]. However, changes in strength ratios [Andrade et al., 2016] and increases in proprioceptive errors [Weerakkody et al., 2017] that occur with fatigue can predispose to injury. This is particularly pertinent to high level overhead or throwing athletes, who can suffer with a range of shoulder injuries [Cowderoy et al., 2009, Gaber et al., 2014].

The recovery of an athlete after training induced muscle fatigue and return to play (RTP) following injury are two important current concepts. The link between increased training load, which induces muscle fatigue, and injury is well established [Jones et al., 2017]. The identification of objective measures, which provide a reliable indication of recovery status within the training environment, would therefore be useful in allowing maximisation of training gains without disproportionately increasing the risk of injury. Objective measures are arguably more useful than subjective ones as the reliability of self-reported workload data has been questioned [Black et al., 2016]. RTP decisions following injury can also be difficult due to the possible conflict of interest between multiple stakeholders, particularly within the professional athletic population [Shrier et al., 2014]. In this scenario a surrogate measure for upper limb performance would similarly be helpful in informing RTP decisions [Clover et al., 2010].

Grip strength is associated 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]. It correlates highly with shoulder external rotation strength [Horsley et al., 2016] and it is known to activate key shoulder girdle muscles including supraspinatus and infraspinatus [Alizadehkhaiyat et al., 2011, Sporrong et al., 1995, 1996]. Indeed a sustained grip contraction induces significant fatigue in a number of shoulder girdle muscles [Hawkes et al., 2015], the inference being that kinetic chain principles require a stable shoulder prior to activation of distal muscle groups. Measuring grip strength is straightforward and produces reliable results which are easy to record [Coldham et al., 2006]. Furthermore, the equipment is both portable and affordable making its measurement convenient.

Recently there is increasing interest within elite sport rehabilitation in the use of grip strength as an objective measure of upper limb performance. However, at present, little is understood about the relationship between grip strength, shoulder muscle fatigue and subsequent recovery. This relationship must be defined if grip strength is to be considered a barometer for upper limb performance or recovery following either fatigue or injury. Therefore, the primary aim of this study was to evaluate the role of grip strength as a surrogate measure for monitoring upper limb recovery from fatigue following an exhausting exercise protocol. The hypothesis was that grip strength would correlate highly with EMG indices of fatigue: a decrease in grip strength was expected following an exhausting shoulder exercise protocol, with both grip strength and muscle fatigue then expected to recover following a rest period.

**2. METHODS**

**2.1 Participants**

Twenty healthy participants including 10 males and 10 females with no previous history of shoulder pathology and a normal clinical examination were recruited into the study. Anthropometric details for the study group were as follows: mean age was 25.5±7.5yr, mean mass 72.8±11.3kg and mean height 172.0±9.1cm. The dominant arm was tested in all cases. The study received approval from the institutional research ethics committee and informed consent was obtained from all participants.

**2.2 Strength Measurements**

Grip strength was measured using a Jamar dynamometer (Biometrics Ltd., UK). Subjects were tested seated on a chair with their hips and knees flexed to 90o; shoulder adducted; elbow flexed to 90o; and wrist and forearm in the neutral position. Maximal shoulder elevation strength in the scapula plane was measured using a shoulder Nottingham Mecmesin Myometer (Mecmesin Ltd., UK). Participants were tested in an upright position with feet shoulder width apart; shoulder elevated to 90o in the scapula plane (30o anterior to coronal plane); elbow extended; and forearm and wrist in neutral. Subjects were instructed to exert maximal effort over a 3s period for all strength measurements. Three trials were performed and the average taken as the maximum voluntary contraction (MVC). Verbal encouragement was provided with participants being encouraged to exceed the previous measurement [Baratta et al. 1998].

**2.3 EMG Instrumentation**

A Telemyo DTS system (Noraxon Inc., USA) was used for EMG signal acquisition. Analysis was performed off-line using the associated MR3 software (Noraxon Inc., USA). The activity in 15 shoulder girdle muscles was recorded. Surface electrodes were used for the anterior deltoid (AD), middle deltoid (MD), posterior deltoid (PD), upper trapezius (UT), middle trapezius (MT), lower trapezius (LT), teres major (TM), upper fibres of latissimus dorsi (ULD), lower fibres of latissimus dorsi (LLD), pectoralis major (PM), teres major (TM) and biceps brachii (BB). The surface electrodes were disposable, pre-gelled Ag/AgCl bipolar electrodes with a conducting area of 10 mm diameter and inter-electrode distance of 20mm (Noraxon Inc., USA). Electrodes were placed in accordance with accepted anatomical criteria [Cram et al., 1998, Prakash et al., 2006, Steenbrink et al., 2006]. Cross talk was limited by using appropriately sized electrodes which were positioned parallel to the muscle fibres. Fine wire electrodes were used to record the activity of the supraspinatus (SSP), infraspinatus (ISP), and subscapularis (SUBS). Bipolar disposable hook wire electrodes (SPES Medica s.r.l. Battipaglia, Italy) were inserted aseptically into the muscle bellies via a single hypodermic needle [Kadaba et al., 1992, Noraxon, 2008]. Signals were differentially amplified, digitised at a sampling rate of 3000 Hz and band-pass filtered in accordance with international guidance ([10–500]Hz for surface electrodes and [10–1500]Hz for fine wire electrodes). ECG contamination was removed using the adaptive cancellation algorithm pre-loaded within the MR3 software. Manual muscle testing was used to confirm electrode placement and the validity of the EMG signal. Those signals of poor quality, as determined by their signal to noise ratio, were excluded.

**2.4 EMG Testing Protocol**

Muscle fatigue was measured during a shoulder elevation isometric contraction performed in the scapula plane at 25% of the MVC. The testing position employed was the same as that used to measure shoulder elevation MVC (see section 2.2). The contraction was sustained for 60s or until failure (defined as a drop of > 5% force for > 5s). Participants were provided with real time visual feedback via a PC screen displaying the Mecmesin Emperor Lite Force and Torque Data Acquisition Software (Mecmesin Ltd., UK). The software allowed participants to view their force generation and the target level as defined by their MVC25%. It also allowed any failure of the contraction to be identified by highlighting any drop in force of > 5% from target. An isometric contraction ensured a stable motor neurone pool, which is a necessary prerequisite for a contraction when studying fatigue [Hagg, 1992, Merletti et al., 1991]. A submaximal contraction (ie MVC25%) is common to the majority of fatigue studies as it ensures comparisons between individuals are valid. In order to study the temporal change in the frequency throughout the contraction it has to be possible to maintain the contraction for a sufficient time period (ie 60 seconds). Low intensity contractions can result in variation in the motor unit pool as motor units are recruited and de-recruited throughout the contraction [Farina et al., 2006]. Conversely, high intensity contractions cannot be maintained for a sufficient period of time. A MVC25% was therefore chosen as an appropriate compromise, which has previously been accepted within the literature [Hawkes et al., 2014]. Optimal rest time has not been defined for upper limb studies of this nature. A 10 minute rest period was chosen as this has previously been evaluated in the literature [Lariviere et al., 2003, Oliveira et al., 2008].

Subjects undertook the fatigue contraction at 3 different time points. An initial recording was measured pre-exertion (Fat-Baseline). The second recording was made after subjects completed a shoulder exercise regime which was undertaken until exhaustion (Fat-Exhaustion). This exhaustion protocol involved 5 repetitions of shoulder elevation first in the sagittal plane (flexion) and then in the coronal plane (abduction) which were continuously repeated. The exercise was performed with a dumbbell in hand (the weight of which was set at 50% of shoulder elevation MVC rounded to the nearest 1kg). Failure of this exhaustion protocol was defined as the inability of subjects to complete any further cycles of shoulder elevation. All subjects continuously performed this protocol until they reached the failure point. Subjects then had a 10-minute recovery period whilst they remained seated with their arms in their laps with no activity. A final fatigue contraction was then performed post-recovery (Fat-Recovery). Grip strength measurements were performed at baseline (Grip-Baseline), immediately after the shoulder exercise protocol (Grip-Exhaustion) and following the rest period (Grip-Recovery). FIGURE 1 provides a schematic representation of the testing protocol.

**2.5 Data Management and Statistical Analysis**

Fast Fourier Transformation was performed to allow analysis of the EMG signal power spectrum. The median frequency (MDF) was then calculated in 1s epochs throughout the fatiguing contraction. Theoretically the median frequency has the best immunity to noise than the mean [Hof, 1991, Stulen et al., 1981]. The initial MDF was then normalised relative to the start value and the mean rate of change (Slope%/min), as assessed by linear regression, was used as the fatigue index [Alizadehkhaiyat et al., 2007a, Alizadehkhaiyat et al., 2007b, 2009, Hawkes et al., 2015, Merletti et al., 1991]. Results are expressed as mean ± standard deviation (SD) or as standard error of the mean (SEM) as appropriate. All the fatigue index data (Slope%/min) was analysed in SPSS (version 21). Data normality was tested using the Shapiro-Wilk test. A repeated measures ANOVA was used to identify differences in the fatigue index as dependent variable across the three testing conditions (Fat-Baseline, Fat-Exhaustion, and Fat-Recovery). Significance level was set at p<0.05.

**3. RESULTS**

All participants completed the testing protocol with no termination of any of the fatiguing contractions (Fat-Baseline, Fat-Exhaustion or Fat-Recovery) early due to failure.

**3.1 Strength**

Mean Grip-Baseline was 38.0±11.8kg, mean Grip-Exhaustion was 34.1±9.1kg and mean Grip-Recovery was 37.8±10.5kg. An ANOVA indicated significant differences between testing scenarios (F=7.851; p=0.005) with post-hoc testing indicating Grip-Exhaustion was significantly lower than Grip-Baseline (p=0.012) and Grip-Recovery (p=<0.001). FIGURE 2 illustrates the grip strength in the different testing scenarios.

**3.2 Fatigue**

TABLE 1 presents mean MDF slopes %/min; and relevant comparisons for all study participants within the different testing scenarios. Significantly greater fatigue was seen in AD, MD, PD, and SSP in the Fat-Exhaustion contraction as compared to the Fat-Baseline contraction (p=<0.001-0.043). Further significantly more fatigue was seen in the AD, MD, PD, UT, MT, LT, SA, and SSP in the Fat-Recovery contraction as compared to the Fat-Baseline contraction (p=0.001-0.043). Significantly greater fatigue was seen during the Fat-Recovery contraction for the MT, LT, SA, and BB as compared to the Fat-Exhaustion contraction (p=0.008-0.038). There were no significant differences in fatigue across the testing scenarios for TM, ULD, LLD, PM, ISP, and SUBS. FIGURE 3 and 4 demonstrate the normalised MDF slopes for selected muscles in the different testing scenarios.

**4. DISCUSSION**

The glenohumeral joint relies heavily on balanced muscular force generation to maintain stability owing to its limited osseous congruity [Lugo et al., 2008]. Furthermore, optimal scapula positioning is necessary to ensure ideal muscle lengths, efficient force production and the establishment of a stable platform for arm movement [McQuade et al., 1998, Tsai et al., 2003]. Fatigued muscles can consequently disrupt the normal glenohumeral force couples as well as the scapulohumeral rhythm, predisposing to injury. Andrade identified a change in internal-external rotation shoulder strength ratios before and after a shoulder fatigue protocol in a study of 10 elite handball players [Andrade et al., 2016]. Fatigue is also known to increase proprioceptive errors, as demonstrated in amateur cricket players, which can contribute to shoulder injuries particularly in overhead or throwing athletes [Weerakkody et al., 2017, Zanca et al., 2015]. Indeed, injuries are more common in the second half of games, thought to be due to the impact of fatigue [Fuller et al., 2016]. In throwing athletes subacromial impingement can occur, in addition to glenohumeral internal rotation deficit (GIRD) which can be associated with instability, labral lesions, internal impingement and partial articular sided rotator cuff tears [Cowderoy et al., 2009, Gaber et al., 2014].

Power grip is known to activate key shoulder girdle muscles given the inter-link between body segments as governed by kinetic chain principles [Alizadehkhaiyat et al., 2007a, Alizadehkhaiyat et al., 2007b, 2009, Hawkes et al., 2015, Sporrong et al., 1995, 1996]. The results of this study indicate that grip strength significantly decreased following an exhausting shoulder exercise protocol. Strength then recovered to baseline following a 10 min rest period indicating that performance level was restored to the pre-exhaustion levels. However, as outlined below, examination of the EMG fatigue results indicates that this restoration of performance level does not correspond to recovery of the fatigued shoulder girdle muscles.

The AD, MD, PD, SSP showed significantly greater signs of fatigue in the Fat-Exhaustion contraction as compared to the Fat-Baseline contraction. This was expected given the exercise protocol involved cyclical shoulder elevation, which corresponded with the prime movement of these muscles. There were no differences in levels of fatigue for the UT, MT, LT, SA, BB between the Fat-Baseline and Fat-Exhaustion contractions. These results are consistent with other studies within the literature. Minning et al. studied the fatigue of the UT, LT, SA and MD, in healthy subjects, during an isometric contraction at 90o of elevation in the scapula plane at 60% MVC. The rates of fatigue were highest in the MD as compared to the other muscles [Minning et al., 2007]. Nieminen et al. studied the order of fatigue induced changes in the shoulder musculature in 10 healthy subjects during an isometric flexion task performed at 90o of humeral elevation.  The deltoid SSP and ISP were the first muscles to show signs of fatigue [Nieminen et al., 1995].

There were no differences in levels of fatigue for the AD, MD, PD, SSP between the Fat-Exhaustion and the Fat-Recovery contraction. The MDF for all muscles remained highly negative, indicating substantial ongoing fatigue. This indicates that these muscles did not demonstrate any EMG signs of fatigue recovery after the prescribed rest period. Furthermore, the MT, LT, SA and BB showed significantly more fatigue in the Fat-Recovery contraction, as compared to the Fat-Exhaustion contraction. This was an unexpected finding. The initial hypothesis was that muscle fatigue would recover at least to some extent following the rest period. However, during the Fat-Recovery contraction, additional recruitment of the periscpaular muscles (MT, LT, SA) and elbow flexor (BB) was observed as indicated by their increased signs of fatigue. It is proposed that this reflects a reorganisation in upper limb movement strategy with adaptations occurring to protect fatigued muscles (i.e. glenohumeral elevators).

Comparable adaptations have previously been reported in the literature. Qin [Qin et al., 2014] demonstrated, using a motion tracking system, that a fatigue protocol results in changes to movement patterns that aim to reduce the load on the fatigued shoulder girdle. Similar results were reported by Fuller [Fuller et al., 2008] following a repetitive reaching task. Cowley [Cowley et al., 2017] reported proximal fatigue caused a significant increase in trunk lean, reduced humeral elevation, and increased elbow flexion. The implication is that despite the recovery in performance level following rest, a fundamental alteration in movement strategy can remain. Caution is therefore needed when solely using grip strength as a surrogate for recovery following fatigue due to potential ongoing susceptibility to injury. There was no significant fatigue across the testing positions for the TM, LD-U, LD-L or PM. This was expected given the nature of the testing position and the known function of the muscles. Similar results were seen for the ISP and SUBS. The ISP showed a trend towards increased fatigue in the Fat-Exhaustion and Fat-Recovery contractions although statistical significance was not reached.

**5. CONCLUSION:**

Grip strength was significantly lower following an exhausting shoulder exercise protocol, however it recovered to baseline following a rest period. Conversely, EMG indices of fatigue did not recover. Additional fatigue was seen in the periscpaular muscles and elbow flexors, which reflects a reorganisation of movement strategy with adaptations occurring to protect fatigued muscles. In conclusion, whilst performance level was restored following the rest period, it was achieved by a reorganisation of movement strategy. Susceptibility to injury therefore still exists if grip strength alone is used as a barometer for monitoring upper limb performance.

**REFERENCES:**

 Alizadehkhaiyat O, Fisher AC, Kemp GJ, Frostick SP. Strength and fatigability of selected muscles in upper limb: assessing muscle imbalance relevant to tennis elbow. J Electromyogr Kinesiol. 2007;17(4):428-36.

Alizadehkhaiyat O, Fisher AC, Kemp GJ, Vishwanathan K, Frostick SP. Assessment of functional recovery in tennis elbow. J Electromyogr Kinesiol. 2009;19(4):631-8.

Alizadehkhaiyat O, Fisher AC, Kemp GJ, Vishwanathan K, Frostick SP. Shoulder muscle activation and fatigue during a controlled forceful hand grip task. J Electromyogr Kinesiol. 2011;21(3):478-82.

Alizadehkhaiyat O, Fisher AC, Kemp GJ, Vishwanathan K, Frostick SP. Upper limb muscle imbalance in tennis elbow: a functional and electromyographic assessment. J Orthop Res. 2007;25(12):1651-7.

Andrade MS, de Carvalho Koffes F, Benedito-Silva AA, da Silva AC, de Lira CA. Effect of fatigue caused by a simulated handball game on ball throwing velocity, shoulder muscle strength and balance ratio: a prospective study. BMC Sports Sci Med Rehabil. 2016;8:13.

Baratta RV, Solomonow M, Zhou BH, Zhu M. Methods to reduce the variability of EMG power spectrum estimates. J Electromyogr Kinesiol. 1998;8(5):279-85.

Black GM, Gabbett TJ, Cole MH, Naughton G. Monitoring Workload in Throwing-Dominant Sports: A Systematic Review. Sports Med. 2016;46(10):1503-16.

Bohannon RW. Hand-grip dynamometry predicts future outcomes in aging adults. J Geriatr Phys Ther. 2008;31(1):3-10.

Bradley JP, Tibone JE. Electromyographic analysis of muscle action about the shoulder. Clin Sports Med. 1991;10(4):789-805.

Clover J, Wall J. Return-to-play criteria following sports injury. Clin Sports Med. 2010;29(1):169-75.

Coldham F, Lewis J, Lee H. The reliability of one vs. three grip trials in symptomatic and asymptomatic subjects. J Hand Ther. 2006;19(3):318-26.

Cowderoy GA, Lisle DA, O'Connell PT. Overuse and impingement syndromes of the shoulder in the athlete. Magn Reson Imaging Clin N Am. 2009;17(4):577-93.

Cowley JC, Gates DH. Proximal and distal muscle fatigue differentially affect movement coordination. PloS ONE. 2017;12(2):e0172835.

Cram JR, Kasman GS, Holtz J. Introduction to surface electromyography. Gaithersburg, Md.: Aspen Publishers; 1998.

De Luca CJ. Myoelectrical manifestations of localized muscular fatigue in humans. Crit Rev Biomed Eng. 1984;11(4):251-79.

Dimitrova NA, Dimitrov GV. Interpretation of EMG changes with fatigue: facts, pitfalls, and fallacies. J Electromyogr Kinesiol. 2003;13(1):13-36.

Farina D, Zennaro D, Pozzo M, Merletti R, Laubli T. Single motor unit and spectral surface EMG analysis during low-force, sustained contractions of the upper trapezius muscle. Eur J Appl Physiol. 2006;96(2):157-64.

Fuller CW, Taylor AE, Raftery M. Should player fatigue be the focus of injury prevention strategies for international rugby sevens tournaments? Br J Sports Med. 2016;50(11):682-7.

Fuller JR, Lomond KV, Fung J, Cote JN. Posture-movement changes following repetitive motion-induced shoulder muscle fatigue. J Electromyogr Kinesiol. 2009;19(6):1043-52.

Gaber S, Zdravkovic V, Jost B. [The throwing shoulder]. Orthopade. 2014;43(3):223-9.

Glousman R. Electromyographic analysis and its role in the athletic shoulder. Clin Orthop Relat Res. 1993(288):27-34.

Gowan ID, Jobe FW, Tibone JE, Perry J, Moynes DR. A comparative electromyographic analysis of the shoulder during pitching. Professional versus amateur pitchers. Am J Sports Med. 1987;15(6):586-90.

Hagg GM. Interpretation of EMG spectral alterations and alteration indexes at sustained contraction. J Appl Physiol. 1992;73(4):1211-7.

Hawkes DH, Alizadehkhaiyat O, Kemp GJ, Fisher AC, Roebuck MM, Frostick SP. Electromyographic assessment of muscle fatigue in massive rotator cuff tear. J Electromyogr Kinesiol. 2015;25(1):93-9.

Hof AL. Errors in frequency parameters of EMG power spectra. IEEE Trans Biomed Eng. 1991;38(11):1077-88.

Horsley I, Herrington L, Hoyle R, Prescott E, Bellamy N. Do changes in hand grip strength correlate with shoulder rotator cuff function? Shoulder Elbow. 2016;8(2):124-9.

Jones CM, Griffiths PC, Mellalieu SD. Training Load and Fatigue Marker Associations with Injury and Illness: A Systematic Review of Longitudinal Studies. Sports Med. 2017;47(5):943-74.

Kadaba MP, Cole A, Wootten ME, McCann P, Reid M, Mulford G, et al. Intramuscular wire electromyography of the subscapularis. J Orthop Res. 1992;10(3):394-7.

Lariviere C, Gravel D, Arsenault AB, Gagnon D, Loisel P. Muscle recovery from a short fatigue test and consequence on the reliability of EMG indices of fatigue. Eur J Appl Physiol. 2003;89(2):171-6.

Lugo R, Kung P, Ma CB. Shoulder biomechanics. Eur J Radiol. 2008;68(1):16-24.

McQuade KJ, Dawson J, Smidt GL. Scapulothoracic muscle fatigue associated with alterations in scapulohumeral rhythm kinematics during maximum resistive shoulder elevation. J Orthop Sports Phys Ther. 1998;28(2):74-80.

Merletti R, Lo Conte LR, Orizio C. Indices of muscle fatigue. J Electromyogr Kinesiol. 1991;1(1):20-33.

Minning S, Eliot CA, Uhl TL, Malone TR. EMG analysis of shoulder muscle fatigue during resisted isometric shoulder elevation. J Electromyogr Kinesiol. 2007;17(2):153-9. 34. Nieminen H, Takala EP, Niemi J, Viikari-Juntura E. Muscular synergy in the shoulder during a fatiguing static contraction. Clin Biomech (Bristol, Avon). 1995;10(6):309-17.

Noraxon. Kinesiological Fine Wire EMG. A practical introduction to fine wire EMG applications. 2008; https://www.velamed.com/wp-content/uploads/2017/08/Fine\_Wire\_EMG.pdf [Accessed 15/12/17].

Prakash KM, Fook-Chong SM, Leoh TH, Dan YF, Nurjannah S, Tan YE, et al. The lower subscapular nerve conduction studies and utilisation in brachial plexopathy evaluation. J Neurol Sci. 2006;247(1):77-80.

Qin J, Lin JH, Faber GS, Buchholz B, Xu X. Upper extremity kinematic and kinetic adaptations during a fatiguing repetitive task. J Electromyogr Kinesiol. 2014;24(3):404-11.

Sayer AA, Syddall HE, Martin HJ, Dennison EM, Roberts HC, Cooper C. Is grip strength associated with health-related quality of life? Findings from the Hertfordshire Cohort Study. Age Ageing. 2006;35(4):409-15.

Shrier I, Safai P, Charland L. Return to play following injury: whose decision should it be? Br J Sports Med. 2014;48(5):394-401.

Sporrong H, Palmerud G, Herberts P. Hand grip increases shoulder muscle activity, An EMG analysis with static hand contractions in 9 subjects. Acta Orthop Scand. 1996;67(5):485-90.

Sporrong H, Palmerud G, Herberts P. Influences of handgrip on shoulder muscle activity. Eur J Appl Physiol Occup Physiol. 1995;71(6):485-92.

Steenbrink F, de Groot JH, Veeger HE, Meskers CG, van de Sande MA, Rozing PM. Pathological muscle activation patterns in patients with massive rotator cuff tears, with and without subacromial anaesthetics. Man Ther. 2006;11(3):231-7.

Stulen FB, DeLuca CJ. Frequency parameters of the myoelectric signal as a measure of muscle conduction velocity. IEEE Trans Biomed Eng. 1981;28(7):515-23.

Syddall H, Cooper C, Martin F, Briggs R, Aihie Sayer A. Is grip strength a useful single marker of frailty? Age Ageing. 2003;32(6):650-6.

Tsai NT, McClure PW, Karduna AR. Effects of muscle fatigue on 3-dimensional scapular kinematics. Arch Phys Med Rehabil. 2003;84(7):1000-5.

Weerakkody N, Allen T. The effects of fast bowling fatigue and adhesive taping on shoulder joint position sense in amateur cricket players in Victoria, Australia. J Sports Sci. 2017;35(19):1954-62.

**TABLE 1.** Normalised mean MDF slopes (%/min) in the difference fatiguing contractions for all study subjects with appropriate comparisons.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | Fat-Baseline |  | Fat-Exhaustion |  | Fat-Recovery |  | Comparisons |
|   | Mean\* | SEM |   | Mean\* | SEM |   | Mean\* | SEM |   | F | p value□ | Scenario | p value∆ |
| AD | -20.3 | 1.7 |  | -36.5 | 3.5 |  | -31.1 | 2.4 |  | 14.005 | **<0.001** | Base vs Exh | **<0.001** |
|  |  |  | Base vs Rec | **0.002** |
|  |  |  | Exh vs Rec | 0.096 |
| MD | -17.7 | 1.6 |  | -28.5 | 3.5 |  | -29.0 | 2.9 |  | 8.755 | **0.003** | Base vs Exh | **0.011** |
|  |  |  | Base vs Rec | **0.002** |
|  |  |  | Exh vs Rec | 0.998 |
| PD | -14.9 | 2.3 |  | -24.6 | 4.2 |  | -28.2 | 3.3 |  | 8.801 | **0.001** | Base vs Exh | **0.020** |
|  |  |  | Base vs Rec | **0.001** |
|  |  |  | Exh vs Rec | 0.188 |
| UT | -8.3 | 2.1 |  | -16.1 | 3.6 |  | -19.0 | 3.0 |  | 7.034 | **0.008** | Base vs Exh | 0.057 |
|  |  |  | Base vs Rec | **0.001** |
|  |  |  | Exh vs Rec | 0.154 |
| MT | -9.1 | 2.4 |  | -8.8 | 2.6 |  | -17.9 | 2.8 |  | 3.693 | **0.036** | Base vs Exh | 0.085 |
|  |  |  | Base vs Rec | **0.043** |
|  |  |  | Exh vs Rec | **0.019** |
| LT | -10.2 | 2.7 |  | -8.7 | 2.7 |  | -18.4 | 2.1 |  | 4.319 | **0.022** | Base vs Exh | 0.660 |
|  |  |  | Base vs Rec | **0.021** |
|  |  |  | Exh vs Rec | **0.008** |
| SA | -18.0 | 2.3 |  | -22.5 | 2.1 |  | -24.8 | 2.9 |  | 5.362 | **0.010** | Base vs Exh | 0.266 |
|  |  |  | Base vs Rec | **0.003** |
|  |  |  | Exh vs Rec | **0.038** |
| TM | -14.0 | 4.5 |  | -12.8 | 4.9 |  | -24.6 | 4.4 |  | 2.510 | 0.104 | Base vs Exh | N/A |
|  |  |  | Base vs Rec | N/A |
|  |  |  | Exh vs Rec | N/A |
| LD-U | -17.6 | 3.2 |  | -17.5 | 3.8 |  | -26.0 | 2.8 |  | 3.677 | 0.054 | Base vs Exh | N/A |
|  |  |  | Base vs Rec | N/A |
|  |  |  | Exh vs Rec | N/A |
| LD-L | -17.3 | 5.7 |  | -16.2 | 3.0 |  | -21.5 | 3.4 |  | 1.600 | 0.221 | Base vs Exh | N/A |
|  |  |  | Base vs Rec | N/A |
|  |  |  | Exh vs Rec | N/A |
| PM | -8.4 | 5.4 |  | -18.1 | 6.4 |  | -21.3 | 3.7 |  | 1.840 | 0.175 | Base vs Exh | N/A |
|  |  |  | Base vs Rec | N/A |
|  |  |  | Exh vs Rec | N/A |
| BB | -8.6 | 4.9 |  | -12.2 | 2.5 |  | -18.2 | 2.5 |  | 4.327 | **0.021** | Base vs Exh | 0.405 |
|  |  |  | Base vs Rec | **0.021** |
|  |  |  | Exh vs Rec | **0.020** |
| SSP | -18.8 | 1.3 |  | -40.8 | 9.7 |  | -34.8 | 4.1 |  | 5.321 | **0.032** | Base vs Exh | **0.043** |
|  |  |  | Base vs Rec | **0.007** |
|  |  |  | Exh vs Rec | 0.504 |
| ISP | -16.1 | 2.7 |  | -25.6 | 5.0 |  | -24.2 | 2.9 |  | 3.962 | 0.054 | Base vs Exh | N/A |
|  |  |  | Base vs Rec | N/A |
|  |  |  | Exh vs Rec | N/A |
| SUBS | -10.9 | 4.6 |  | -22.9 | 10.7 |  | -23.2 | 8.4 |  | 1.068 | 0.484 | Base vs Exh | N/A |
|  |  |  | Base vs Rec | N/A |
|   |   |   | Exh vs Rec | N/A |

\* Values are mean MDF slope (%/min); □ repeated measures ANOVA comparing testing scenarios with relevant ∆ post-hoc testing as appropriate. Bold values indicate significant differences; **Exh**: Exhaustion; **Rec**: Recovery; **AD**: Anterior Deltoid; **MD**: Middle Deltoid; **PD**: Posterior Deltoid; **UT**: Upper Trapezius; **MT**: Middle Trapezius; **LT**: Lower Trapezius: **SA**: Serratus Anterior; **LD-U**: Latissimus Doris (Upper Fibres); **LD-L**: Latissimus Doris (Lower Fibres); **TM**: Teres Major; **PM**: Pectoralis Major; **BB**: Biceps Brachii; **SSP**: Supraspinatus; **ISP**: Infraspinatus; **SUBS**: Subscapularis.

**Captions to Figures**

**FIGURE 1.** Schematic representation of testing protocol

**FIGURE 2.** Box and whiskers plots comparing grip strength in the different testing scenarios. Grey box represents interquartile range; black line mean; error bars minimum and maximum values; \* indicated significant differences

**FIGURE 3.** Normalsed MDF for selected muscles during the different fatigue contractions

**FIGURE 4.** Normalsed MDF for selected muscles during the different fatigue contractions

**Figures**

Baseline fatigue contraction (Fat-Baseline)

Baseline grip strength (Grip-Baseline)

Shoulder exercise protocol performed until exhaustion

Cyclical shoulder elevation with dumbbell in hand weight of which approximated 50% MVC to the nearest 1kg. Failure point defined as the inability of subjects to complete any further cycles.

Exhaustion fatigue contraction (Fat-Exhaustion)

Exhaustion grip strength (Grip-Exhaustion)

10 min rest period

Subjects seated with arms in lap and no activity

Recovery fatigue contraction (Fat-Recovery)

Recovery grip strength (Grip-Recovery)

**FIGURE 1.**

\*

\*

**FIGURE 2.**

Fat-Baseline Fat-Exhaustion Fat-Recovery

**FIGURE 3.**

Fat-Baseline Fat-Exhaustion Fat-Recovery

**FIGURE 4.**