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Revision 1

An electromyographic evaluation of dual role breathing and upper body muscles in response to front crawl swimming

Running head: Breathing muscle EMG responses to swimming

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## Abstract

The upper-body trunk musculature is key in supporting breathing, propulsion and stabilization during front crawl swimming. The aim of this study was to determine if the latissimus dorsi, pectoralis major and serratus anterior contributed to the development of inspiratory muscle fatigue observed following front crawl swimming. Fourteen trained swimmers completed a 200-m front crawl swim at 90% of race pace. Maximal inspiratory and expiratory mouth pressures (P<sub>I</sub>max and P<sub>E</sub>max) were assessed before (baseline) and after each swim and electromyography was recorded from the three muscles. Post swim P<sub>I</sub>max fell by 11% ( $P < 0.001$ ,  $d = 0.57$ ) and the median frequency (MDF: a measure of fatigue) of the latissimus dorsi, pectoralis major and serratus anterior fell to 90% ( $P = 0.001$ ,  $d = 1.57$ ), 87% ( $P = 0.001$ ,  $r = -0.60$ ) and 89% ( $P = 0.018$ ,  $d = 1.04$ ) of baseline, respectively. The fall in serratus anterior MDF was correlated with breathing frequency ( $r = 0.675$ ,  $P = 0.008$ ) and stroke rate ( $r = 0.639$ ,  $P = 0.014$ ). The results suggest that the occurrence of inspiratory muscle fatigue was partly due to fatigue of these muscles and that breathing frequency and stroke rate particularly affect the serratus anterior.

Key words: median frequency, fatigue, inspiratory mouth pressure

## Introduction

It has been suggested that a duality of muscle function exists during front crawl swimming with some upper body trunk muscles that are responsible for propulsion and stabilization also being responsible for supporting the elevated demands of breathing (Brown & Kilding, 2011; Lomax & Castle, 2011). The muscles most likely to share this duality of function are the latissimus dorsi, pectoralis major and serratus anterior (Kendall et al., 2005; Nuber et al., 1986; Pink et al., 1991).

Electromyography (EMG) has shown that the latissimus dorsi and pectoralis major are key in moving the body over the arm during the propulsive underwater phase of the front crawl swimming stroke (Nuber et al., 1986; Pink et al., 1991). Of the upper body trunk muscles the activity of the latissimus dorsi (as a percentage of maximum) is equaled only by the inferior portion of the rectus abdominis. The average intensity of the latissimus dorsi contraction over the course of a stroke cycle may be as high as 92% of that observed during a maximum isometric contraction (Clarys, 1985). Along with the flexor carpi ulnaris, biceps brachii and triceps brachii, the latissimus dorsi is also key in maintaining swimming speed (Ikuta et al., 2012). The next substantial upper body trunk muscle contribution during front crawl comes from the pectoralis major. Typical activation per stroke cycle is around 37-43% of that obtained during a maximal contraction (Clarys, 1985). Conversely, the serratus anterior is associated with a lower peak activation per stroke cycle but a continued and greater sustainment of the average activation (20-40%) during sub-maximal swimming (Pink et al., 1991). This sustained activity reflects the role of the serratus anterior in ensuring shoulder joint stability and preparation for the next propulsive phase (Pink et al., 1991; Wadsworth & Bullock-Saxton, 1997).

As well as providing information on muscle activation, EMG, and specifically the frequency or spectral content and amplitude of the signal, can also be used to monitor fatigue (De Luca, 1997). Irrespective of whether spectral parameters or amplitude measures are used to evaluate muscle activity, a number of upper body and limb muscles have been shown to fatigue in response to maximal front crawl swimming (Aujouannet et al., 2006; Figueiredo et al., 2013; Ikuta et al., 2012; Lomax et al., 2014; Stirn et al., 2011). Of relevance to this study are the latissimus dorsi and pectoralis major findings: no studies have examined the fatigability of the serratus anterior during front crawl swimming. The latissimus dorsi has been shown to fatigue in response to maximal 100-m and 200-m front crawl swimming (Ikuta et al., 2012; Stirn et al., 2011). Similar observations have been made in the pectoralis major in response to 100-m and 200-m maximal front crawl swimming (Figueiredo et al., 2013; Ikuta et al., 2012; Stirn et al., 2011) as well as arms only front crawl sprinting (Lomax et al., 2014).

As the latissimus dorsi, pectoralis major and serratus anterior all contribute to the front crawl stroke and the production of inspiratory muscle force, it is relevant to ask whether the occurrence of inspiratory muscle fatigue, which is now well documented following race-paced (Brown & Kilding, 2011; Lomax et al., 2012; Thomaidis et al., 2009) and sub-race paced (Lomax & Castle, 2011; Lomax et al., 2013; Lomax & McConnell, 2003) front crawl swimming, is at least partly due to fatigue of these muscles. With the exception of one study showing that pre-induced inspiratory muscle fatigue resulted in latissimus dorsi fatigue which persisted during a short flat-out arms only front crawl sprint (Lomax et al., 2014), no studies have attempted to

identify which of these three dual function muscles become fatigued during front crawl swimming.

The present study was designed to address this question. Given that swimming at 90% of 200-m front crawl race pace is sufficient to induce inspiratory muscle fatigue (Lomax & Castle, 2011; Lomax & McConnell, 2003; Lomax et al., 2013), we hypothesized that inspiratory muscle fatigue would be evident after such a swim and that it would be caused (at least partly) by fatigue of the latissimus dorsi, pectoralis major and serratus anterior. Consequently, we expected a reduction in the median frequency (MDF, a frequency content measure) and integrated EMG (iEMG an amplitude measure) of the EMG signals recorded from the latissimus dorsi, pectoralis major and serratus anterior during the post swim P<sub>I</sub>max maneuver compared with the baseline P<sub>I</sub>max maneuver. Conversely, we did not expect to observe evidence of expiratory muscle fatigue.

## Materials and methods

### Subjects

Fourteen collegiate swimmers (7 males) volunteered for this study. Mean  $\pm$  SD for age, body mass and stature were  $20.3 \pm 3.5$  years,  $79.0 \pm 8.2$  kg,  $179.6 \pm 4.7$  cm, respectively for males, and  $21.6 \pm 5.2$  years,  $65.9 \pm 12.2$  kg,  $164.3 \pm 5.1$  cm, respectively for females. Barometric pressure, air temperature, water temperature and humidity were  $765.0 \pm 8.0$  mmHg,  $25.3 \pm 1.2^\circ\text{C}$ ,  $27.9 \pm 0.4^\circ\text{C}$ , and  $63.6 \pm 9.4\%$ , respectively. All swimmers were well-trained collegiate swimmers with a seasonal personal best of  $140.2 \pm 21.9$  seconds (males:  $126.6 \pm 4.6$  seconds; females:  $150.5 \pm 13.5$  seconds) for 200-m front crawl. All were well hydrated prior to, and avoided training or competition for at least 24 hours before, testing. None had any history of cardio-pulmonary disease. Subjects provided written informed consent and local ethical approval was obtained before the start of the study.

### Testing procedure

Before any swimming testing took place subjects undertook a pulmonary familiarization session during which standing maximal inspiratory mouth pressure (P<sub>I</sub>max) and standing maximal expiratory mouth pressure (P<sub>E</sub>max) maneuvers were practiced (RPM, Micro Medical, Rochester, UK). The nose was occluded throughout and a 60 second rest separated each effort. P<sub>I</sub>max was measured from residual volume (RV) and P<sub>E</sub>max from total lung capacity (TLC). Reliability was deemed present when three technically proficient maneuvers within 5 cmH<sub>2</sub>O were obtained (Lomax & Castle, 2011). In addition, forced vital capacity, forced expired volume in one second and peak expiratory and inspiratory flow rates were recorded from TLC or RV, where applicable, with the nose occluded, and for demographic purposes only. Measurements were made in accordance with ATS/ERS guidelines.

On a separate day participants undertook a front crawl swim in a swimming flume (SwimEx 600-T Therapy Pool, length 4.2 m, width 2.3 m and depth 1.5 m) preceded by a brief warm-up. Before this swimmers provided their season's best 200-m front crawl swim time so that target velocity could be calculated. Target velocity was set to 90% of each swimmer's time. The velocity of the flume ( $\text{m}\cdot\text{s}^{-1}$ ) was calculated by

dividing the target distance of 200-m by target time in seconds. The time taken to complete 200-m was then calculated and swimmers swam for this length of time.

Before and immediately after the 200-m swim subjects performed standing P<sub>Imax</sub> and P<sub>E<sub>max</sub></sub> maneuvers on poolside: up to three pre swim P<sub>Imax</sub> maneuvers were recorded to ensure that baseline, as identified during the familiarization session, was obtained. Surface EMG was recorded from the pectoralis major, latissimus dorsi and serratus anterior during each P<sub>Imax</sub> and P<sub>E<sub>max</sub></sub> maneuver. In addition, each 200-m swim was recorded (digital camera interfaced to ShowBiz software, ArcSoft, Fremont, USA) for subsequent analysis of stroke rate and breathing frequency. The total number of stroke cycles (one left and one right arm stroke) was divided by time (s) to convert to cycles per second (Hz) and then multiplied by 60 to convert to cycles per minute. Breathing frequency was calculated as total number of breaths taken per swim divided by time in seconds multiplied by 60 (Lomax et al., 2011).

#### Electromyography data collection

Surface EMG was recorded on the right side of the body. The pectoralis major, latissimus dorsi and serratus anterior were chosen because of their significant contribution to both the front crawl arm stroke (Nuber et al., 1986; Pink et al., 1991) and deep inspirations (Kendall et al., 2005). In addition, activation of these muscles during maximal inspiratory and expiratory efforts was checked and confirmed at the start of the study. The electrode sites were identified and marked in accordance with the methods of Criswell (2011). Specifically, the clavicular placement was used for the pectoralis major with the electrode placed at a slight oblique angle two cm below the clavicle and medial to the axillary fold. The latissimus dorsi was placed four cm below the inferior tip of the scapula halfway between the lateral edge of the torso and the spine and at a slight oblique angle. The serratus anterior was placed horizontally below the axillary area level with the inferior tip of the scapula and just medial of the latissimus dorsi (Criswell, 2011).

The electrode sites were first shaved and then rubbed with an alcohol wipe to minimize the impedance of the skin (Criswell, 2011). Waterproof bipolar electrodes with an interelectrode distance of two cm (REF SX230, Biometrics Ltd, Newport, Wales) were adhered to the prepared site using medical grade adhesive tape (T350, Biometrics Ltd, Newport, Wales). The EMG signals were recorded with a sampling rate of 1000 Hz, preamplified ( $\times 1000$ ) and filtered with a bandwidth of 20-450 Hz. Input impedance was  $> 10^{15}$  Ohms and the common mode rejection ratio at 60 Hz dB was greater than 96 dB. Each electrode was connected to a portable data acquisition unit (DataLOG, Biomtrics Ltd, Newport, Wales) by a five metre waterproof cable (SX230W, Biometrics Ltd, Newport, Wales). The ground electrode (R206 Ground Strap Assembly, Biometrics Ltd, Wales) was fixed over the styloid process of the radius and interfaced with the data acquisition unit via a five metre waterproof cable. To minimize cable movement and hence interference with the signal, all cables were fixed to the skin via medical grade adhesive tape and supported by a cable running across the width of the flume above the swimmer.

#### EMG signal processing

DataLog software (DataLog software version 5.06, Biometrics Ltd, Newport, Wales) was used for signal processing. P<sub>Imax</sub> and P<sub>E<sub>max</sub></sub> maneuvers were separated into an active and inactive phase. The active phase was defined as the EMG signal which

was at least 30% of the local maximum energy. This represents regions of high activation and excludes regions of low activation and is consistent with the methods of Stirn et al. (2011). The local maximum energy was determined using the average rectified value calculated using a window length of 250 ms. The mean MDF was obtained by fast fourier transformation per active phase using a window length of 64 ms. The same window length was used to determine iEMG. Post swim P<sub>I</sub>max and P<sub>E</sub>max data were expressed as a percentage of baseline per muscle (relative) as well as expressed in absolute values for MDF and iEMG (Hz and mv respectively).

#### Data analysis

Data were assessed for normality using a Shapiro-Wilk test and homogeneity of variance using Levene's test. Reliability was assessed using the coefficient of variation (CV). Specifically, reliability was assessed for absolute (cmH<sub>2</sub>O) P<sub>I</sub>max and P<sub>E</sub>max values (familiarization and baseline experimental values).

Paired samples t-tests and Wilcoxon Singed Rank tests assessed differences in absolute baseline and post swim P<sub>I</sub>max and P<sub>E</sub>max values, as well as EMG data. Friedman's ANOVAs assessed differences in relative post swim MDF values between muscles during P<sub>I</sub>max and P<sub>E</sub>max maneuvers. Pearson's (r) and Spearman's (rho) correlation coefficients assessed for correlations between the fall in MDF and the magnitude of inspiratory muscle fatigue per muscle, stroke rate and breathing frequency.

Where relevant, and for parametric data, effect sizes were calculated using Cohen's *d* with an effect size of 0.2 deemed small, 0.5 medium and 0.8 and above large (Cohen, 1988). For non-parametric data effect sizes were calculated using *r*, whereby *r* was the *z* score divided by the square root of the total number of observations, with an effect size of .1 small, .3 medium, .5 large (Field, 2013). Significance was set as  $P \leq 0.05$  as a priori, and statistical analyses were conducted using IBM SPSS Statistics version 21 (Chicago, IL, USA). Unless otherwise stated, data are expressed as mean  $\pm$  SD. 95% confidence intervals (CI) were also calculated.

#### Results

Achieved swimming velocity, baseline pulmonary data and swimming kinematics data can be found in table 1.

\*\*Table 1 here\*\*

The reliability of P<sub>I</sub>max and P<sub>E</sub>max was good (4.6% and 7.0%, respectively). Post swim P<sub>I</sub>max declined by  $11 \pm 7\%$  from  $148 \pm 31$  cmH<sub>2</sub>O to  $131 \pm 29$  cm H<sub>2</sub>O ( $t = 5.744$ ,  $P < 0.001$ ,  $d = 0.57$ ) whereas P<sub>E</sub>max changed little from  $138 \pm 42$  cmH<sub>2</sub>O to  $136 \pm 35$  cmH<sub>2</sub>O post swim ( $t = 0.517$ ,  $P = 0.614$ ).

Post swim P<sub>I</sub>max MDF was lower than baseline P<sub>I</sub>max in the pectoralis major ( $87 \pm 11\%$ ,  $z = -3.180$ ,  $P = 0.001$ ,  $r = -0.60$ ), latissimus dorsi ( $90 \pm 9\%$ ,  $t = -4.353$ ,  $P = 0.001$ ,  $d = 1.57$ ) and serratus anterior ( $89 \pm 15\%$ ,  $t = -2.718$ ,  $P = 0.018$ ,  $d = 1.04$ ) (figure1). These changes were not significant between muscles ( $X^2_{(2)} = 0.143$ ,  $P = 0.981$ ). Post swim P<sub>I</sub>max iEMG data were highly variable being  $88 \pm 71\%$  in the latissimus dorsi ( $z = -1.452$ ,  $P = 0.147$ ,  $r = -0.27$ ),  $90 \pm 46\%$  in the pectoralis major ( $t = 0.854$ ,  $P = 0.408$ ,  $d = 0.31$ ) and  $126 \pm 64\%$  in the serratus anterior ( $t = -1.510$ ,  $P =$

0.155,  $d = -0.57$ ). However, absolute iEMG (mv) in the latissimus dorsi was lower during post swim P<sub>I</sub>max ( $z = -1.961$ ,  $P = 0.050$ ,  $r = -0.37$ ). Table 2 displays absolute P<sub>I</sub>max MDF values and table 3 absolute P<sub>I</sub>max iEMG values.

**\*\*Figure 1 here\*\***

Post swim P<sub>E</sub>max MDF remained unchanged in the pectoralis major ( $99 \pm 12\%$ ,  $t = -.301$ ,  $P = 0.768$ ,  $d = 0.12$ ) and serratus anterior ( $94 \pm 10\%$ ,  $t = -2.072$ ,  $P = 0.059$ ,  $d = 0.85$ ) but fell in the latissimus dorsi ( $93 \pm 12\%$ ,  $z = -2.291$ ,  $P = 0.022$ ,  $r = -0.43$ ) (figure 1). There were no differences in P<sub>E</sub>max MDF between muscles ( $X^2_{(2)} = 1.000$ ,  $P = 0.694$ ). Post swim P<sub>E</sub>max iEMG data were highly variable being  $70 \pm 38\%$  in the latissimus dorsi ( $z = -0.078$ ,  $P = 0.937$ ,  $r = -0.02$ ),  $65 \pm 54\%$  in the pectoralis major ( $z = -0.089$ ,  $P = 0.929$ ,  $r = -0.02$ ) and  $55 \pm 59\%$  in the serratus anterior ( $z = -0.345$ ,  $P = 0.730$ ,  $r = -0.07$ ). Table 2 displays absolute P<sub>E</sub>max MDF values and table 3 absolute P<sub>E</sub>max iEMG values.

**\*\*Table 2 here\*\***

**\*\*Table 3 here\*\***

Unsurprisingly stroke rate and breathing frequency were related ( $r = 0.958$ ,  $P < 0.001$ ). A correlation was observed between the change in MDF of the serratus anterior in post swim P<sub>I</sub>max and breathing frequency (breaths·min<sup>-1</sup>:  $r = .675$ ,  $P = 0.008$ ) and the change in MDF of the serratus anterior in post swim P<sub>I</sub>max and stroke rate (cycles·min<sup>-1</sup> & Hz:  $r = .639$ ,  $P = 0.014$ ) (figure 2).

**\*\*Figure 2 here\*\***

## Discussion

The aim of this study was to determine if the occurrence of inspiratory muscle fatigue in response to 200-m front crawl swimming was attributed to fatigue of the predominant dual function upper body front crawl trunk muscles. We hypothesized that fatigue of the latissimus dorsi, pectoralis major and serratus anterior would occur in response to swimming at 90% of 200-m front crawl race-pace and that this would be evidenced in P<sub>I</sub>max. As P<sub>I</sub>max fell by 11% following the swim and this was associated with a leftward shift in latissimus dorsi, pectoralis major and serratus anterior MDF (figure 1), we can accept our hypothesis. However, the high variability in iEMG data (table 3) suggests that iEMG was not a particularly sensitive indicator of inspiratory muscle fatigue in the muscles selected

The observed changes in MDF are consistent with fatigue. In accordance with Henneman's size principle, submaximal contractions recruit small diameter, low threshold motor units (and hence slow twitch muscle fibres) rather than large diameter, high threshold motor units (and hence fast twitch muscle fibres) (MacIntosh et al., 2006). As fatigue ensues other units are recruited to compensate for any loss in force (Carpentier et al., 2001; Enoka et al., 1989). This is supported by an increase in motor unit synchronization and action potential size (Bigland-Ritchie, 1981; De Luca, 1997; Stirn et al., 2011) causing iEMG to increase (Masuda et al., 1999; Potvin & Bent, 1997; Stephens & Taylor, 1972; Stirn et al., 2011). During maximal



contractions fast twitch muscle fibres are recruited (MacInosh et al., 2006) along with further potential motor unit synchronisation (Bigland-Ritchie, 1981; Hermens et al., 1992). When all relevant motor units have been recruited there are no additional units remaining that can replace those fatigued. Furthermore, these motor units will remain fatigued until an adequate period of recovery has occurred. This could be in excess of 10 minutes depending on motor unit phenotype (Enoka et al., 1989).

In addition to the recruitment of smaller motor units, a P<sub>Imax</sub> maneuver would be expected to recruit large diameter, high threshold motor units as it is a maximal maneuver. As these motor units have faster conduction velocities than smaller diameter, low threshold motor units they experience a greater (Kupa et al., 1995) and more rapid (Komi & Tesch, 1979) fall in the frequency of the power density spectrum. This is because conduction velocity is slowed as a result of metabolic byproduct accumulation (e.g. increased hydrogen and potassium ion accumulation), which alters the properties of the muscle membrane (Dimitrova & Dimitrov, 2003; Kupa et al., 1995; Masuda et al., 1999). Consequently, one would expect a fall in both MDF (Kupa et al., 1995; Komi & Tesch, 1979) and iEMG (Bilodeau et al., 2003; Stephens & Taylor, 1972) when contractions require a large input from fatiguing fast twitch muscle fibres.

Fast twitch muscle fibres have been shown to account for around 52-68% and 65% of latissimus dorsi and pectoralis major composition, respectively (Paoli et al., 2013; Srinivasan et al., 2007): unfortunately little is reported about the composition of the serratus anterior. The fall in post swim P<sub>Imax</sub> MDF in the current study therefore probably reflects fatigue predominantly of high threshold motor units induced by the preceding swim. Such fatigue could reflect the demands of moving the body through the water and the physiological consequences of the stroke-induced restricted breathing pattern. Furthermore, although we observed a fall in absolute (mv) latissimus dorsi iEMG during the post swim P<sub>Imax</sub> maneuver (table 3), the difference was masked when normalized (%) to baseline because of the large variability. This suggests that MDF is a more sensitive indicator of inspiratory muscle fatigue than iEMG in the muscles studied. However, it should be acknowledged that the window length chosen when processing iEMG was short (64 ms) but was chosen to reflect the quasi-isometric nature of MIP and MEP maneuvers. The variation in iEMG could be reduced by increasing the window length (e.g. >100 ms) thereby making iEMG more reflective of the isometric, rather than the dynamic, proportion of the MIP and MEP contractions (Burden, 2008).

An interesting observation in the current study was the correlation between the change in serratus anterior P<sub>Imax</sub> MDF and breathing frequency and stroke rate. Our data indicate that the greater the breathing frequency and stroke rate, which themselves are intimately linked (coefficient of determination of 92% in the current study), the greater the leftward shift in MDF. In support of this we observed coefficients of determination between the magnitude of serratus anterior fatigue, and breathing frequency and stroke rate of 46% and 41% respectively.

Pink et al. (1991) have suggested that the serratus anterior muscle is likely to be particularly susceptible to fatigue during swimming because of its continuous activity. If recruitment of the serratus anterior is suboptimal there is an elevated risk of subacromial impingement and swimmers suffering from this syndrome demonstrate

delayed recruitment of the serratus anterior compared with uninjured swimmers (Wadsworth & Bullock-Saxton, 1997). Furthermore, swimmers who breathe unilaterally rather than bilaterally are at a greater risk of developing shoulder impingement on their breathing side (Yani & Hay, 2000). It is possible that increasing breathing frequency will predispose the serratus anterior to fatigue because of its role in maintaining rib-cage and scapula stability (Pink et al., 1991; Wadsworth & Bullock-Saxton, 1997). If this increase changes breathing from a bilateral to unilateral pattern the risk of shoulder injury will be increased (Yani & Hay, 2000). This raises an interesting question regarding a possible link between serratus anterior fatigue, inspiratory muscle fatigue and the potential for subacromial impingement. We cannot confirm whether or not such a link does exist but think it worthy of investigation.

Although fatigue was observed in the latissimus dorsi, pectoralis major and serratus anterior this does not preclude fatigue of other muscles from contributing to the fall in P<sub>I</sub>max. The P<sub>I</sub>max maneuver is a holistic maneuver and the pressure recorded at the mouth will reflect the collective activity of all the muscles recruited (Gibson, 1995). We are unable to identify if other muscles were fatigued and contributed to the fall in P<sub>I</sub>max and do not rule out this possibility. It should also be noted that we observed a fall in latissimus dorsi MDF during the post swim P<sub>E</sub>max maneuver (table 2 and figure 1) but no change in absolute P<sub>E</sub>max following the swim. This indicates that the latissimus dorsi contributes to pressure generation during the P<sub>E</sub>max maneuver but that fatigue of the motor units/muscle fibres sampled within this muscle could be compensated and so P<sub>E</sub>max was unaffected. The same is likely of the serratus anterior. Although the fall in P<sub>E</sub>max MDF was non-significant it only just missed statistical significance ( $P = 0.059$ ) and demonstrated a large effect size ( $d = 0.85$ ) which suggests that a type II error occurred. In contrast, the MDF of the pectoralis major was unchanged post swim during the P<sub>E</sub>max maneuver suggesting that there is scope for fatigued motor units to be derecruited with little impact on P<sub>E</sub>max and MDF.

In conclusion, our results extend previous work demonstrating inspiratory muscle fatigue following sub-maximal front crawl swimming (Lomax & McConnell, 2003; Lomax & Castle, 2011; Lomax et al., 2014). Our data indicate that the MDF of the latissimus dorsi, pectoralis major and serratus anterior were all lower during the post swim versus baseline P<sub>I</sub>max maneuver which is indicative of fatigue. However, it was only the serratus anterior which demonstrated any correlation between the magnitude of fall in P<sub>I</sub>max MDF and stroke rate and breathing frequency. . Our data also indicate that unlike MDF, iEMG is too variable to be used as an indicator of fatigue (at least when using short processing window lengths) during holistic respiratory muscle strength assessments. Furthermore, as the magnitude of serratus anterior fatigue experienced was correlated with breathing frequency and stroke rate, the serratus anterior is particularly susceptible to changes in breathing pattern and stroke rate.

#### Perspective

Although inspiratory muscle fatigue has been well documented in response to swimming, and in particular front crawl, the muscles contributing to its development had not previously been examined. This study demonstrates that the latissimus dorsi, pectoralis major and serratus anterior are all implicated in its development.

Moreover, the serratus anterior is particularly susceptible to the impact of stroke kinematic changes. Given that this muscle is vital in maintaining shoulder joint stability and that subacromial impingement can occur if activation is suboptimal, or breathing pattern changes from a bilateral pattern to a unilateral pattern, any possible link between inspiratory muscle fatigue and the propensity for shoulder injury should be examined.

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Table 1. Baseline pulmonary data and 200-m front crawl kinematic data: group (n=14), male (n=7) and female (n=7) mean  $\pm$  SD

Variable	Group	Males	Females
Maximal inspiratory mouth pressure (cmH <sub>2</sub> O)	148 $\pm$ 31	156 $\pm$ 18	139 $\pm$ 39
Maximal expiratory mouth pressure (cmH <sub>2</sub> O)	138 $\pm$ 42	169 $\pm$ 25	111 $\pm$ 37
Forced vital capacity (l)	4.15 $\pm$ 0.80	4.82 $\pm$ 0.71	3.70 $\pm$ 0.49
Forced expired volume in one second (l)	3.84 $\pm$ 0.61	4.34 $\pm$ 0.50	3.51 $\pm$ 0.43
Peak expiratory flow rate (l·min <sup>-1</sup> )	427 $\pm$ 86	506 $\pm$ 38	375 $\pm$ 65
Peak inspiratory flow rate (l·min <sup>-1</sup> )	371 $\pm$ 122	584 $\pm$ 28	259 $\pm$ 22
Percentage of seasonal personal best achieved	89.1 $\pm$ 1.4	88.3 $\pm$ 1.6	90.0 $\pm$ 0.0
Achieved swimming velocity (m·s <sup>-1</sup> )	1.32 $\pm$ 0.37	1.40 $\pm$ 0.06	1.20 $\pm$ 0.12
Breathing frequency (breaths·min <sup>-1</sup> )	21 $\pm$ 3	21 $\pm$ 3	21 $\pm$ 4
Stroke rate (cycles·min <sup>-1</sup> )	32 $\pm$ 5	32 $\pm$ 4	29 $\pm$ 4
Stroke rate (Hz)	0.53 $\pm$ 0.08	0.53 $\pm$ 0.06	0.52 $\pm$ 0.09

Table 2. Absolute MDF (Hz) data for PImax and PEmax per muscle (group mean  $\pm$  SD)

	Baseline			Post swim		
	Mean $\pm$ SD	SEM	95% CI	Mean $\pm$ SD	SEM	95% CI
<b>Pectoralis major (Hz)</b>						
PImax	63 $\pm$ 9	2.405	58-68	54 $\pm$ 7**	1.871	50-57
PEmax	67 $\pm$ 13	3.474	60-74	65 $\pm$ 10	2.673	60-70
<b>Latissimus dorsi (Hz)</b>						
PImax	70 $\pm$ 14	3.741	63-77	62 $\pm$ 12**	3.207	56-68
PEmax	78 $\pm$ 18	4.811	69-87	72 $\pm$ 16*	4.276	64-80
<b>Serratus anterior (Hz)</b>						
PImax	60 $\pm$ 7 <sup>f</sup>	1.871	56-64	53 $\pm$ 8*	2.138	49-57
PEmax	57 $\pm$ 8	2.138	53-61	54 $\pm$ 8	2.138	50-58

different to baseline \* $P < 0.05$ , \*\* $P < 0.01$ . MDF = median frequency. PImax = maximal inspiratory mouth pressure. PEmax = maximal expiratory mouth pressure.

Table 3. Absolute iEMG (mv) data for PImax and PEmax per muscle (group mean  $\pm$  SD)

	Baseline			Post swim		
	Mean $\pm$ SD	SEM	95% CI	Mean $\pm$ SD	SEM	95% CI
Pectoralis major (mv)						
PImax	3.94 $\pm$ 3.21	0.858	2.26-5.62	3.72 $\pm$ 2.36	0.631	2.48-4.96
PEmax	2.90 $\pm$ 2.53	0.676	1.58-4.22	3.71 $\pm$ 2.11	0.564	2.60-4.82
Latissimus dorsi (mv)						
PImax	1.99 $\pm$ 2.83	0.756	0.51-3.47	1.01 $\pm$ 0.64*	0.171	0.67-1.35
PEmax	1.24 $\pm$ 1.36	0.364	0.53-1.95	1.09 $\pm$ 0.52	0.139	0.82-1.36
Serratus anterior (mv)						
PImax	1.77 $\pm$ 1.42	0.380	1.03-2.51	1.93 $\pm$ 1.70	0.454	1.04-2.82
PEmax	1.68 $\pm$ 1.19	0.318	1.06-2.30	1.77 $\pm$ 1.15	0.307	1.17-2.37

different to baseline \* $P < 0.05$ . iEMG = integrated electromyography. PImax = maximal inspiratory mouth pressure. PEmax = maximal expiratory mouth pressure.



## Figure legends

Figure 1. The mean and SD MDF value for the pectoralis major, latissimus dorsi and serratus anterior during P<sub>I</sub>max and P<sub>E</sub>max maneuvers post swim.

MDF = median frequency. P<sub>I</sub>max = maximal inspiratory mouth pressure. P<sub>E</sub>max = maximal expiratory mouth pressure.

Significant differences are marked with asterisk, \*\* $P < 0.01$ , \* $P < 0.05$ .

Figure 2. Correlation between stroke rate and breathing frequency (a), the change in MDF of the serratus anterior in post swim P<sub>I</sub>max and breathing frequency (b), and the change in MDF of the serratus anterior in post swim P<sub>I</sub>max and stroke rate (c).

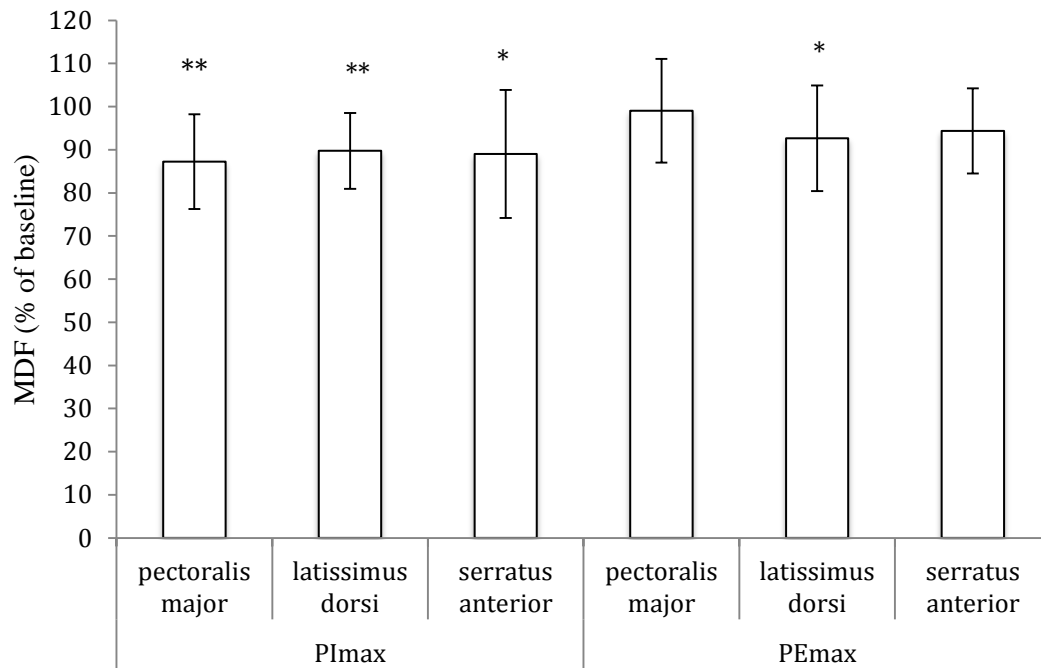
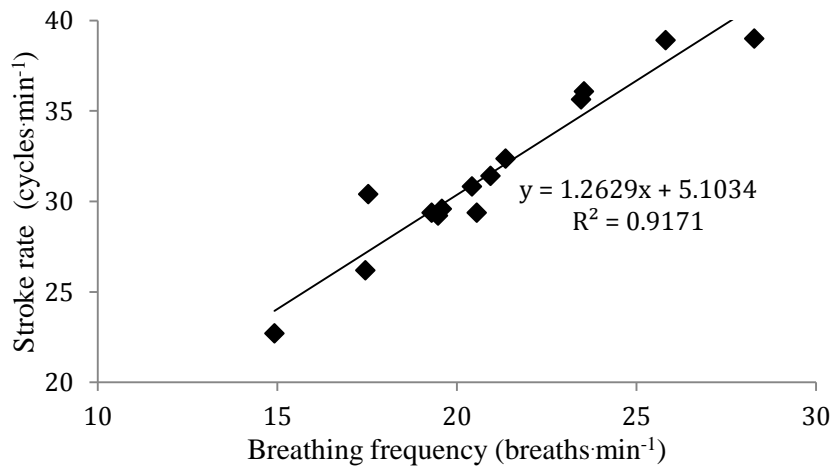


Figure 1. The mean and SD MDF value for the pectoralis major, latissimus dorsi and serratus anterior during PImax and PEmax maneuvers post swim.

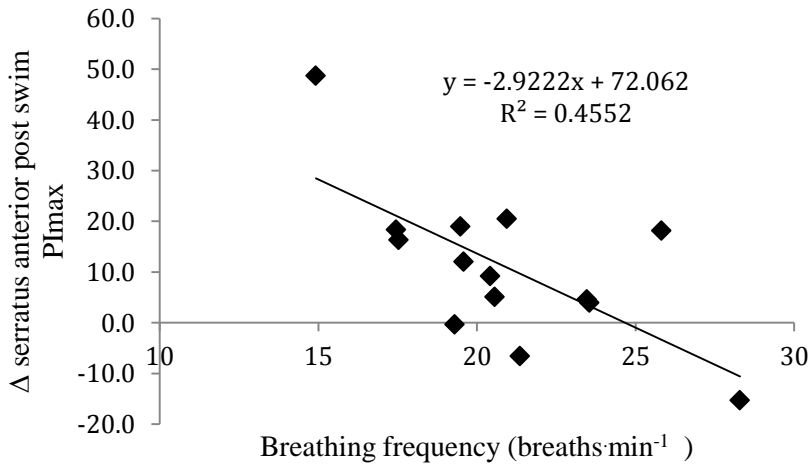
The mean and SD MDF value for the pectoralis major, latissimus dorsi and serratus anterior during PImax and PEmax maneuvers post swim.

MDF = median frequency. PImax = maximal inspiratory mouth pressure. PEmax = maximal expiratory mouth pressure.

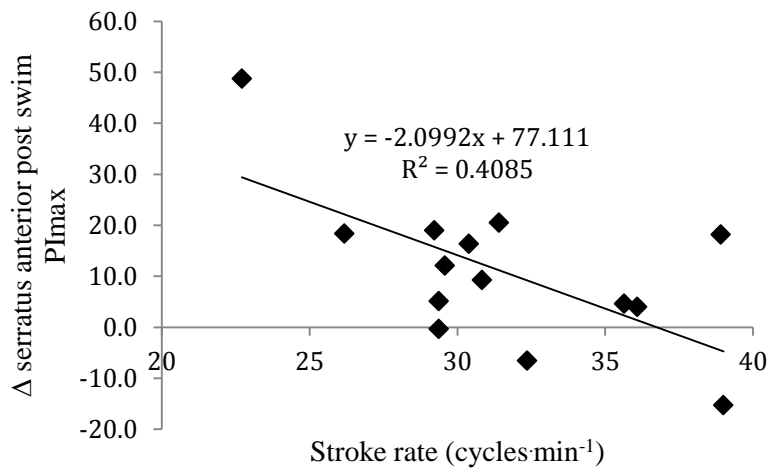
Significant differences are marked with asterisk, \*\* $P < 0.01$ , \* $P < 0.05$ .



a



b



c

Figure 2. Correlation between stroke rate and breathing frequency (a), the change in MDF of the serratus anterior in post swim PImax and breathing frequency (b), and the change in MDF of the serratus anterior in post swim PImax and stroke rate (c).