CHARACTERISING THE INFLUENCE OF PRE-DRIVE LUNG VOLUME ON FORCE AND POWER PRODUCTION DURING ROWING

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by

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Abstract

Purpose: This study evaluated the effect of lung volume at the catch position to force and power outputs during single maximal effort strokes in rowing. Responses were compared when the participants were ‘fresh’ and following specific inspiratory muscle fatigue (IMF). In addition, a single subject pilot study was performed to characterise the changes in intra-thoracic (ITP), intra-abdominal (IAP) and trans-diaphragmatic (P_{di}) pressures during a 30 second maximal effort piece on a rowing ergometer. **Methods:** Nine male rowers of international standard participated in the research. Static force, as well as the power produced during a single stroke were assessed at residual volume (RV), $25\%_{TLC}$, $50\%_{TLC}$, $75\%_{TLC}$, total lung capacity (TLC), and a self-selected lung volume (S-S). Lung volumes were derived from maximal flow-volume loops (MFVLs) and achieved using online real-time feedback. Inspiratory muscle fatigue (IMF) was induced by breathing against an inspiratory load equivalent to 80% baseline maximal inspiratory pressure (MIP), at a breathing frequency (f_B) of 15 breaths per minute, and a duty cycle of 0.6. Expiration was unimpeded. The single subject pilot study was undertaken using balloon catheters to measure ITP, IAP, and P_{di} during a 30 second maximal effort free-rating piece on the ergometer. **Results:** There was no significant effect of lung volume upon either force or power production. The RMF protocol induced a significant reduction in MIP (159.9 ± 70.8 vs. 106.8 ± 58.7 cmH_2O; p = 0.000), but not maximal expiratory pressure (MEP; 159.9 ± 79.2 vs. 166.6 ± 53.0 cmH_2O; p = 0.376). RMF induced a significant reduction in force output with increasing lung volume, across all lung volumes (mean force 1313.4 ± 31.9 vs. 1209.6 ± 45.0N; p < 0.008), but not power (mean power 598.6 ± 31.9 vs. 592.7 ± 45.0W; p > 0.05). Self-selected lung volumes were consistent across all tests for force and power (mean 38.1 ±

6.9% [Force] vs. 28.2 ± 0.6% [Power]; $p > 0.017$). The pilot study indicated that internal pressures fluctuate markedly during maximal effort rowing (pressure, [max, min, average] cmH_2O; IAP [144.69, 7.46, 73.59], ITP [75, -22.65, 15.34], Pdi [111.84, 7.09, 58.83]), suggesting that the trunk muscles play an active role in power production during rowing. **Conclusion:** The present study suggests that there is no significant effect of lung volume on force or power when athletes are in a fresh condition. However, a decrement in force production is present with inspiratory muscle fatigue. Combined with evidence of high internal pressures during maximal effort rowing, these data may indicate a role for the inspiratory muscles in force production during rowing.

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List of Contents

List of Tables

List of Figures

Chapter 1: Introduction

It has long been recognised that experienced rowers synchronise their breathing to rowing stroke rate (Mahler, et al., 1991a, 1991b; Steinacker, et al., 1993); this form of synchronisation is termed entrainment. Steinacker et al. (1993) observed that in five national level oarsmen, breathing pattern was confined to two main breathing patterns; 1) one expiration and one inspiration (one breath) per stroke (1:1), or 2) one complete breath during both drive and recovery (2:1). They also observed that tidal volume (V_T; the volume of each breath) was constrained above a certain power output, with further increases in ventilation being brought about by increases in breathing frequency. Maximal rowing induces a high ventilatory response, and entrainment that is employed during rowing leads to hypoventilation, which does not occur in other sports requiring entrained breathing such as running or cycling (Szal & Schoene, 1989, Siegmund, et al., 1999, Smith, et al., 1996). Steinacker et al. (1993) further concluded that at high work rates, stroke rate may be dictated by the urge to breathe, which reinforces the potent interrelationship between these two factors. Equally, it is also possible that stroke rate may exert ‘control’ over breathing patterns, so that in order to maintain or increase stroke rate, the rower may be forced to adapt their breathing strategy. Tidal volume has been shown to be limited above a certain power output (Steinacker et al., 1993), and it is possible that a restriction of V_T, in order to perform higher stroke ratings, may adversely affect the power that can be produced during the stroke. The principal assumption here is that V_T and power output are positively related, which is currently unknown.

Anecdotal observations on GB squad athletes over a number of years (Al Smith, Richard Godfrey, Rob Shave, Lee Romer; personal communications) have confirmed the presence of entrainment, but have highlighted the large inter-individual variation that exists in the ratio of entrainment. This variation in entrainment ratio has also been highlighted in a number of published articles (Siegmund, et al., 1999; Bonsignore, et al., 1998; Paterson, et al., 1986; Bechbache & Duffin, 1977; Jasinkas, et al., 1980; Mahler, et al., 1991a, 1991b; Steinacker, et al., 1993). One consistent observation, however, is the presence of an inspiratory manoeuvre immediately prior to the catch. It has been suggested that rowers perform this manoeuvre at this point in the rowing stroke to stabilize the thorax (Biersteker, et al., 1986) in preparation for the drive. The potential significance of this inspiration is unknown, but a study by Manning et al. (2000) has shown that when rowers inspire at the catch, the subsequent expiration during the drive leads to a higher intra-abdominal pressure. The authors suggest that high intra-abdominal pressure contributes to a higher spinal stability. It is reasonable to suggest that the presence of a volume of air in the lungs at the catch not only influences spinal stability, but also the efficiency of the transmission of force through the body during the drive (and therefore the power produced during that drive), and the susceptibility to spinal injury.

The present study was designed to assess the influence of pre-drive lung volume upon the forces generated during a single, maximal effort stroke in both the ‘fresh’ and fatigued state. In addition, since the diaphragm is known to be an important core stabilising muscle (Hodges & Gandevia, 2000a), the influence of inspiratory muscle fatigue upon force and power production was evaluated. Two hypotheses will be explored; 1) that force and power will be proportional to lung volume, and 2) specific inspiratory muscle fatigue will cause an overall decrement in force and power production. The present study also enabled the monitoring of a number of other functions. It has been noted previously that although rowers do not incur many injuries, the majority of those that do occur are spinal or rib related (Stallard, 1995). Although intra-abdominal (Manning, et al., 2000) and intra-pleural (Steinacker, et al., 1993) pressures have been previously recorded, no study has yet recorded measurements of trans-diaphragmatic or intra-thoracic pressures during rowing. Accordingly, the present study also examined intra-thoracic and intra-abdominal pressures during maximal effort rowing and during maximal single strokes at different lung volumes. This was undertaken in a single subject as a pilot experiment for future research.

Chapter 2: Review Of Literature

2.1 Rowing & Ergometry

Rowing is not only a major competitive sport, but also a form of physical activity that can enhance all areas of muscular and cardiopulmonary fitness; rowing is also a sport with a relatively low prevalence of injury (Budgett & Fuller, 1989). The performance of an individual or a crew can be measured by their race time, with Olympic regattas and most domestic multi-lane regattas being conducted over a straight 2,000 m course, although longer 'head' races are also contended. A typical regatta performance will last between 320 and 460 seconds, depending upon boat class (Eight, Four, Pair, Single), boat type (sculling [x] or sweep [+/-; denotes coxed/coxless boats]), weight (heavyweight [HWT] or lightweight [LWT]), gender, fitness of individual or crew, technical ability and external factors such as environmental conditions (Ingham, et al., 2002). Races of this duration require high levels of explosive power for the start, and then for this power to be continued, maintained and re-applied through the oar by the oarsman or oarswoman to lever the boat through the water for anywhere up to 300 strokes in any one race. This requires not only a high level of power, but also a certain degree of endurance to continue re-applying the power throughout the race. Rowing is neither a power nor endurance sport, but a unique mixture of the two.

Unfortunately, it remains difficult to accurately assess physiological parameters of performance during 'on-water' rowing, which has contributed to the development of rowing ergometers. Rowing ergometers were developed in an attempt to recreate the movements, feelings and resistances felt during 'on-water' rowing. Since their introduction, these ergometers have been widely used to describe the physiological profiles of rowers, and have been found to be reliable when testing for a race simulation performance (MacFarlane, et al., 1997; Schabort, et al., 1999). Schabort, et al. (1999) concluded that the ergometer was suitable for monitoring rowing performance and for investigating factors that affect performance in short, high-intensity endurance events such as a simulated 2000 m race. Ergometer assessment has allowed group and individual training programs to be monitored and optimised (Kramer, et al., 1994). The resistance created to reproduce the resistance felt during 'on-water' rowing is simulated on most ergometers by rotation of a flywheel. This flywheel is either loaded by friction of a weighted belt, or by air resistance created by rotating vanes; popular versions of these two types of ergometer are the Gjessing (A.S. Haby, Norway) and Concept II (Concept II, Nottingham, UK; Figure 1a) respectively. The Concept II ergometer is the most widely used ergometer for training and assessment within the Great Britain squad, and the UK fitness market in general, as it 'provides a close approximation to the movements of a rowing stroke and allows accurate measurements of the physiological changes produced by the work' (Craven, et al., 1993). However, rowers themselves have criticised the subjective 'feel' that ergometer rowing produces (Mahony, et al., 1999).

There have been advances in ergometer design that increase sport specificity. When in a boat, the athlete or crew allows the boat to move under them, whereas the opposite is the case for ergometer rowing. On the ergometer the loading mechanism and the slide bar are fixed, so the rower has to actively move up and down the slide during the recovery and drive phases of the stroke. Concept II have recently introduced an addition to their ergometer that allows more than one athlete/ergometer to be linked together linearly, as would normally be found in a boat, but also allows the ergometers to be free flowing. This advent allows the rower to stay relatively motionless whilst the ergometer moves around them, as should be the case in the boat. Another ergometer, the RowPerfect (RowPerfect UK, London, UK; Figure 1b), has a freely moving air-braked system. These mechanical variations incorporate the extra elements of skill and feel to control the movement of the free mechanism during the recovery phase (Mahony, et al., 1999). However, this variation in mechanics has proven to produce no statistically significant differences in physiological parameters when compared to 'fixed' air-braked ergometers (Mahony, et al., 1999).

Figure 1a. The Concept II Rowing Ergometer

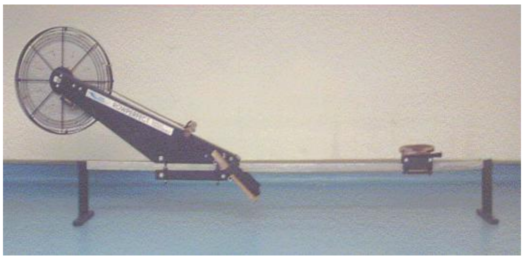

Figure 1b. The RowPerfect Ergometer

The rowing stroke does not have any start or finish point *per se*, but is more a sequence of movements and timings that flow into each other, creating a continuous cycle of actions. During 'on-water' rowing, the 'finish' (Figure 2a) is the point at which the blade is extracted from the water. From here, with the legs flat and back slightly extended beyond 90^{o}, the hands move away from the body until straight where the body then flexes at the pelvis and transfers the athletes' weight onto the footplate (Figure 2b). Then, the legs break at the knees and the boat is allowed to move underneath the crew or individual - the 'recovery' (Figure 2c). During this time, the blade is out of the water and has been 'feathered', which is the backward rotation of the blade handle so that the spoon of the oar is parallel with the water, which happens immediately after the spoon is extracted from the water. As the boat moves under the crew and the legs compress, the blade is then 'squared', which is the forward rotation of the blade so that the spoon of the oar is at right angles to the water. At the time the legs are fully compressed and the blade is square, the blade is then entered into the water behind the perpendicular of the boat to create the 'catch' (Figure 2d). The blade is then loaded by the water and the 'drive' (Figure 2e) is timed with the legs and back extending against the resistance of the water, which propels the boat forwards. Just as the legs are finishing the drive, the back begins to extend and contributes towards the finishing power (Figure 2f). When the legs are fully extended the back is extended to just past the 90^{o}, the blade handle is drawn into the body, the 'finish' is recreated, and the cycle starts again. These phases and postures are recreated on the ergometer, although as there is no blade there is no need for the squaring and feathering actions.


Figure 2a The Finish


Figure 2b The Rock Over


Figure 2c The Recovery


Figure 2d The Catch


Figure 2e The Drive


Figure 2f The ¾ Drive

Although breathing ratios vary, an athlete typically adopts a 1:1 or 2:1 breathing ratio during a complete stroke (breathing ratios and locomotor-respiratory coupling are described in greater depth in Section 2.6). To relate this into Figures 2a-f above, expiration, for either a 1:1 or 2:1 ratio, always occurs throughout the entirety of the drive (Figures 2d-f, back through to 2a). At the finish position, expiration ends and as the rock-over occurs (Figure 2b), and inspiration begins. The difference in ratios takes place during the main body of the recovery (Figure 2c); for a 1:1 ratio, the athlete will only inspire fully once whilst moving to the catch position, whereas during a 2:1 ratio, the athlete will perform a full breathing cycle before inhaling again into the catch, thus performing 2 complete breaths during the rowing stroke.

2.2 The Elite Rower

2.2.1 Anthropometry & Body Mass

Elite rowers differ in biological characteristics when compared to other elite water-borne sportspeople such as canoeists or kayakers (Sklad, et al., 1994); the selection of rowers seems to emphasise stature, whereas that of the kayakers and canoeists emphasises muscular development. However, even within the narrower category of rowing, there are differences in the biological demands of sweep rowing and sculling, and the requirement for considerable ‘active’ body mass is emphasised further if the crew carries a coxswain (Secher, 1990).

Although rowing is a weight-supported sport, the resistance to forward motion of the boat is proportional to the $2/3^{rd}$ power of the mass of the boat and its crew (Secher, 1990). With exceptions to weight-restricted events (lightweight categories have a maximum weight limit of 72.5 kg for males, 59 kg for females), it appears to be beneficial to select rowers with a large muscular body build, as large body mass has been positively related to performance (Secher, et al., 1983). This is to ensure that the larger proportion of mass transported is active muscle rather than the ‘dead weight’ of the boat itself (plus cox where used). A number of attempts have been made to quantifying relationships between anthropometry and muscular and aerobic power.

Various theoretical analyses have suggested relationships between aerobic or muscular power with standing height (Asmussen & Christensen, 1967; cited in Shephard, 1998) and body mass (Secher, 1992), although empirical observations suggest that aerobic power increases as a function of stature (Shephard, et al., 1980). Whatever function of stature is responsible for this, it seems beneficial for rowers to be tall, and competitive success is strongly influenced by mean propulsive power per unit body mass (Deming, et al., 1992; Smith & Spinks, 1995)

Additional to height, it appears beneficial to be long limbed to create extra leverage (Stein, et al., 1983). A recent study by Barrett and Manning (2004) has broken down anthropometric characteristics of rowers and correlated these with rowing performance. Correlations were found with stature, arm span and knee to floor length. It was not noted whether thigh length (and therefore leg length), sitting height or arm length correlated well with race performance. It is understood that, at present, there is no information regarding the influence of height versus limb length; for example, for a given height, long legs/short bodies being as effective as, or better than, short legs/long bodies. In addition, a kinematic and electromyographic study has shown that task learning leads to a longer stroke, higher stroke rating, a better summation of joint forces and a more efficient recovery phase (Marr & Stafford, 1983). Ideally, a high proportion of muscle and relatively low levels of body fat should accompany stature to save moving ‘dead-weight’. The percent body fat of rowers seems to have been decreasing in recent years (Shephard, 1998). When comparing the different classes of boat, sweep oarsmen and oarswomen tend to be taller and heavier than scullers. Where a cox is carried, there are further, albeit smaller, increases in stature and weight (Hirata, 1979; cited in Shephard, 1998).

2.2.2 Pulmonary Function and Dynamics

Studies that have been focused upon rowing in the past have largely revolved around the aerobic capabilities of an athlete, whether this is for predicting performance (Cosgrove, et al., 1999), to study the physiological responses between friction and air-brake ergometry (Mahony, et al., 1999), or to study physiological responses between ergometry and on-water rowing (Bassett, et al., 1984; Bouckaert, et al., 1983; Chenier & Leger, 1991). Performance over 2000 m on a rowing ergometer, or during on-water rowing, is highly dependent upon the functional capacity of both aerobic and anaerobic pathways (Secher, 1973). The relative amount of energy being derived from aerobiosis has been estimated to be approximately 70% for males (Hagerman, et al., 1978) and 88% for females (Pripstein, et al., 1999). However, in shorter rowing events, the aerobic contribution is proportionately smaller; the opposite is the case for longer events (Hagerman, et al., 1978).

There is little doubt that there is great demand placed upon the cardiorespiratory systems of rowers, as competitive sweep rowing is amongst the most physically demanding of the endurance sports. Several previous studies have compared the physiological characteristics of elite rowers to less skilled rowers, giving evidence to suggest that elite rowers have higher levels of maximal oxygen uptake ($\dot{V}O_{2max}$; Secher, et al., 1982), and a higher oxygen consumption ($\dot{V}O_2$) at a blood lactate of 4 mmol.l^{-1} (Roth, et al., 1983; Marx, 1988 - both cited in Cosgrove, et al., 1999). Maximal aerobic capacities of competitive oarsmen are among the highest recorded (Carey, et al., 1974; Di Prampero, et al., 1971; Jackson & Secher, 1976; Saltin & Åstrand, 1967); the absolute $\dot{V}O_{2max}$ of male rowers has been measured in excess of 6.5 $l.min^{-1}$ (or 70 $ml.kg.min^{-1}$; Hagerman, et al., 1978; Steinacker, 1993). Maximal absolute oxygen uptake has been found to have the strongest correlation with performance (Mickelson & Hagerman, 1982; Secher, et al., 1982; Hagerman, 1984; Kramer, et al., 1994; Cosgrove, et al., 1999; Klusiewicz, et al., 1999).

Maximal minute ventilation ($\dot{V}_E$) of male rowers has been found to be greater than 200 $l.min^{-1}$ (Hagerman, et al., 1978; McKenzie & Rhodes, 1982), compared to typical values for untrained males of 100-150 $l.min^{-1}$. Values in excess of 250 $l.min^{-1}$ have been recorded for GB squad open class male rowers (Smith, personal communication). A large maximal $\dot{V}_E$ is advantageous, as breathing not only supplies oxygen (O_2), but also removes carbon dioxide (CO_2). The latter assists in buffering the metabolic acidosis. As approximately 30% of the energy provided for work comes from anaerobic means, there is a need to 'blow off' CO_2 in order to minimise changes in blood and muscle pH. Very large minute volumes must be developed during competition, and selection could favour those with large total and vital lung capacities (Donelly, et al., 1991). However, it has been suggested that there may be some limitation upon breathing frequency (f_B) imposed by the stroke rate during rowing (Donelly, et al., 1991), which could limit $\dot{V}_E$. Hence, the ability to achieve and maintain a high V_T may be an important factor in maintaining adequate $\dot{V}_E$ for O_2 delivery and CO_2 removal. $\dot{V}_E$ also affects oxygenation of the blood through its influence upon blood pH; a decrease in blood pH impairs oxygen loading in the lungs, which may impair oxygen transport to the working muscles.

Peak expiratory flow rates have been found to reach 15 $l.sec^{-1}$ in elite oarsmen, which facilitates the rapid emptying of the lungs. However, some of these individuals also show a plateau in expiratory flow rates during exercise at high work rates (Steinacker, et al., 1993; Carles, et al., 1980 - cited in Shephard, 1998), which could suggest dynamic airway collapse, and/or respiratory muscle fatigue. During submaximal rowing, $\dot{V}_E$ for a given O_2 uptake has been found to be similar to that of cycling and treadmill running (Smith, et al., 1994); however, maximal $\dot{V}_E$ during rowing was lower than the other two modes of exercise. This was statistically significant for non-rowers, but not for elite rowers, suggesting that rowing training may overcome the ventilatory limitations of breathing entrainment imposed by rowing. It is worth noting here that V_T is limited above a certain power output in rowers (Steinacker, et al., 1993), and, for elite rowers, further increases in ventilation must come about through an increase in breathing frequency. Novice rowers may not be able to develop the increase in breathing frequency in order to cope with the ventilatory demands of rowing during the early stages of training. This may explain the differences in maximal ventilation found by Smith, et al. (1994). Since breathing frequency (f_B) may be limited by the stroke rate (Donnelly, et al. 1991), large $\dot{V}_E$ coupled with high expiratory flow rates, or the ability to overcome ventilatory limitations (by increasing breathing frequency), could be amongst the factors that distinguish elite rowers from 'sub-elite' rowers.

The extent to which breathing imposes a limitation to performance during rowing is currently unknown. It is known that entrainment may impose a limitation to efficient gas exchange, but the contribution of the respiratory musculature to force transmission during the drive phase of rowing has received no attention. The sections that follow describe the respiratory system structure and function as a prelude to exploring the potential role of respiratory muscles in force production.

2.3 The Lungs

2.3.1 The Respiratory System Structure

The respiratory system is composed of several organs, each with their own unique function. Essentially, these include the nasal cavities and paranasal sinuses, pharynx, larynx, trachea, bronchi, the lungs and the alveoli.

The nose is the primary passageway for air entering the respiratory system at rest, entering through the nostrils, which opens into the nasal cavity. The space within the nose is referred to as the vestibule, which contains coarse hairs. These capture large airborne particles such as sand, sawdust, and the like, and prevent them from passing through the nasal cavity. The nasal cavity initially filters (via the coarse hairs), warms and humidifies the passing air. The paranasal sinuses, aided by tears draining through various ducts, secrete mucus to help keep the nasal cavity moist and clean. From here, the air passes into the pharynx, which shares its chamber with the digestive tract. The pharynx is divided into three regions; the nasopharynx, the oropharynx and the laryngopharynx. Inspired air passes through these sections of the pharynx and the glottis, entering the larynx. The larynx’s primary function is to surround and protect the glottis; exhaled air passing through the glottis can vibrate the vocal chords, produces sound waves and speech. The secondary function of the larynx is to protect the opening to the trachea (windpipe) where again, the air is filtered.

The trachea is a tough, but flexible tube approximately 2.5 cm in diameter and 11 cm in length. It is covered in a thick layer of mucosa, similar to that found in the nasal cavity, used for capturing any foreign bodies that have escaped filtration. The trachea branches to form the right and left primary bronchi. The right primary bronchi supplies the right lung, and the left primary bronchi supplies the left lung, with the right primary bronchi being larger and descending towards the lungs at a steeper angle than the left; thus most foreign matter that does make its way into the bronchi will enter the right bronchus rather than the left. The primary bronchi are outside of the lungs, and are also referred to therefore as extrapulmonary bronchi.

As the primary bronchi enter the lungs they divide to form secondary bronchi, which then divide further to form tertiary bronchi. Each tertiary bronchus branches several times to form bronchioles. These then branch further to form fine conducting branches called terminal bronchioles; each terminal bronchiole delivers air to a single pulmonary lobule, which is a fine division of the lung. Within each pulmonary lobule, the terminal bronchiole branches to form several respiratory bronchioles. All levels of bronchi from the secondary bronchus down to the respiratory bronchioles are collectively termed intrapulmonary bronchi; the various branches of the bronchi form the bronchial tree (Figure 3).

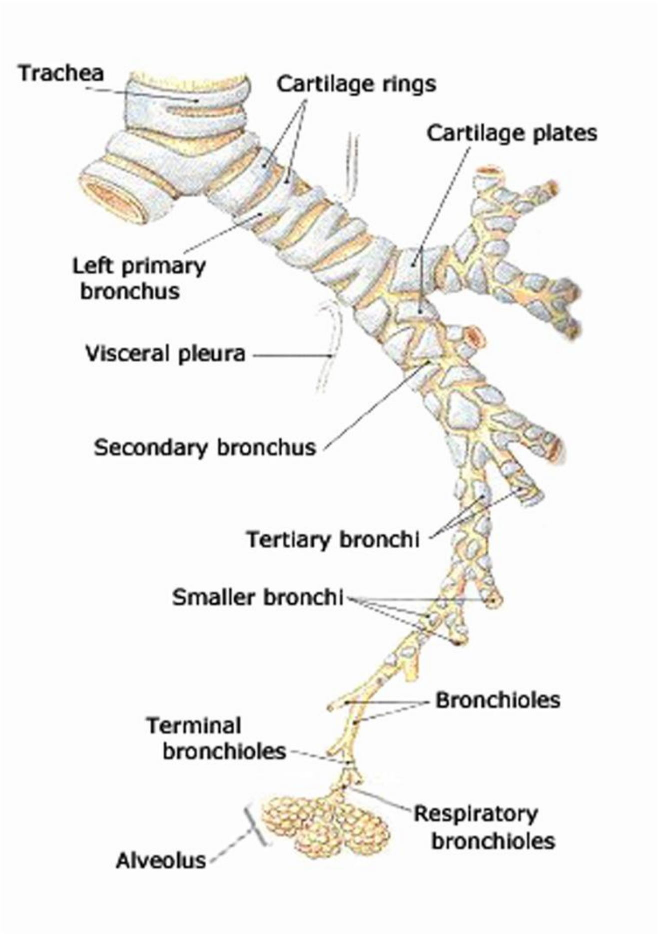

Figure 3. The infrastructure of the lungs

The respiratory bronchioles are the thinnest and most delicate of the bronchial tree, and deliver air to the exchange surfaces of the lungs. Respiratory bronchioles are connected to individual alveoli, and to multiple alveoli along regions called alveolar ducts. These passageways end at alveolar sacs; common chambers connected to multiple individual alveoli, totalling approximately 150 million in each lung. The volume of the lung, and hence the amount of oxygen that the alveoli will come into contact with, changes due to movements of the rib cage and the diaphragm. These movements are responsible for ventilation, or breathing.

2.3.2 Respiratory Physiology

The term respiration generalises two integrated processes: internal and external respiration. Martini (1998) describes external respiration as “all of the processes involved in the exchange of oxygen and carbon dioxide between the interstitial fluids in the body and the external environment.” The goal of external respiration, and the primary function of the respiratory system, is to meet the respiratory demands of living cells (Martini, 1998). The respiratory demand of living cells is the function that drives pulmonary ventilation; the physical movement of air into and out of the lungs. The primary function of pulmonary ventilation is to maintain alveolar ventilation, i.e., air movement into and out of the alveoli. Alveolar ventilation prevents the build up of carbon dioxide (CO_2) and ensures a supply of oxygen great enough to meet the demands of internal respiration; the absorption of oxygen (O_2) by living cells.

Air flows from areas of high pressure to areas of low pressure (Boyle’s Law). The law states:

$$P_1 \times V_1 = P_2 \times V_2$$

Where *P* is the pressure of the air, and *V* is the volume the air is contained in. This law assumes that the temperature of the gas remains constant, but this is not strictly true for ventilation, as the body warms the air that is to be expired. A single respiratory cycle consists of an inhalation (inspiration) and an exhalation (expiration). These two processes involve changes in the volume of the lungs, and hence the pressures within them. It is in response to these pressure changes that the air moves into and out of the respiratory tract.

At the start of the breath, the pressures are identical; therefore there is no movement of air into or out of the lungs. When the thoracic cavity enlarges, the lung volume increases to fill the space created. The pressure within the lungs has decreased, therefore air moves from the atmosphere through the respiratory tract and into the lungs. Air continues to move into the lungs until the volume of the lungs ceases to increase and the pressure within the lungs is the same as the atmosphere. When the thoracic cavity decreases in volume the pressure increases, forcing air out of the lungs and back into the atmosphere. Movements of various muscles, such as the diaphragm and intercostals, have a direct impact on the volume of the lungs.

2.3.3 Respiratory Muscles, Respiratory Cycle & Modes of Breathing

A respiratory cycle is a single cycle of one inspiration and one expiration. The amount of air moved into and out of the lungs in a single respiratory cycle is termed the tidal volume (V_T). There are many skeletal muscles used in respiration, but of these the most important are the diaphragm and the external intercostals, which are used during normal or quiet breathing. Accessory muscles become active when the depth and frequency of breathing is increased, such as in exercise. The accessory muscles include the sternocleidomastoid, serratus anterior, scalenes, transversus thoracis, transversus abdominis, external obliques, internal obliques and the rectus abdominis. These muscles can be seen in Figure 4.

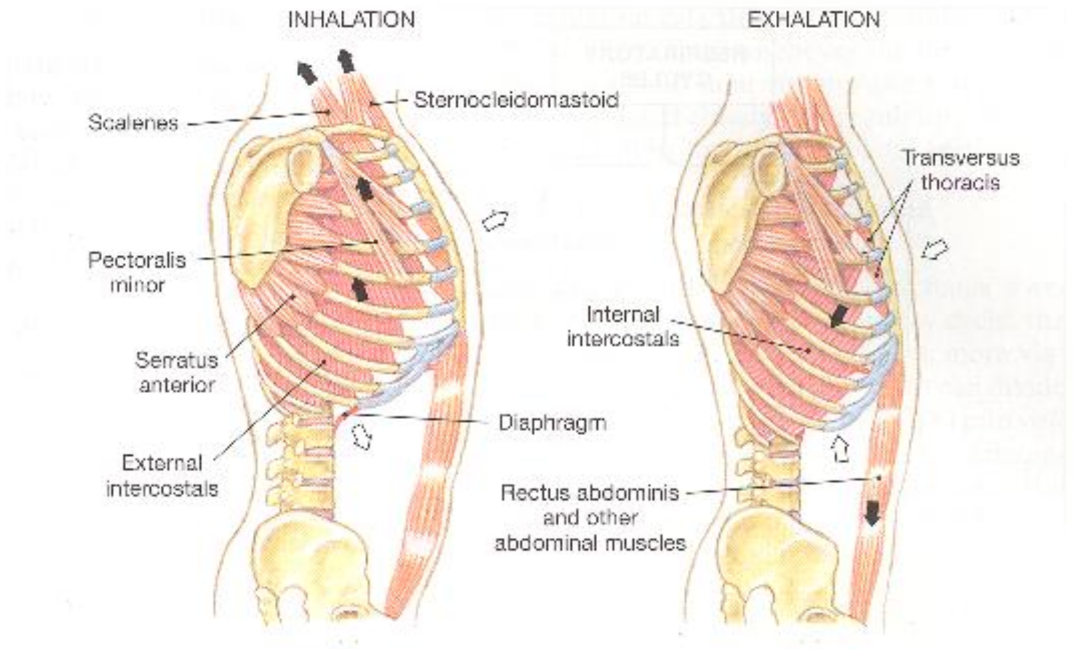

Figure 4. The inspiratory and expiratory muscles

Inhalation is an active process involving the contraction of the inspiratory muscles. Contraction of the diaphragm increases the volume of the thoracic cavity by tensing and tightening its floor, which draws air into the lungs. This is responsible for approximately 75% of air movement in normal quiet breathing (Martini, 1998). The external intercostals assist inhalation by elevating the ribs, accounting for the other proportion of air movement (Martini, 1998). Some accessory muscles (sternocleidomastoids, serratus anterior and the scalenes) can assist the external intercostals. Exhalation can be either passive or active depending upon the level of respiratory activity. When exhalation is active, for example during heavy exercise, it also uses several other muscles. The internal intercostals and transversus thoracis reduce the width and depth of the thoracic cavity, where the abdominal muscles (including the internal and external obliques) the transversus abdominis, and the rectus abdominis can assist the internal intercostals by compressing the abdomen and forcing the diaphragm upward, whilst simultaneously pulling the ribs downward.

The respiratory muscles may be used in various combinations depending largely upon the volume of air that is moving into and out of the lungs. The movements are usually classified as quiet breathing or forced breathing, depending upon muscle activity in the course of a single respiratory cycle (Martini, 1998). In quiet breathing, or eupnoea, inhalation is active, but expiration is passive. As mentioned before, inhalation involves the diaphragm and the external intercostals, although the relative contribution of these muscles varies depending upon the intensity of the breathing. Expansion of the lungs stretches the elastic fibres of the muscles used, additionally, elevation of the rib cage stretches opposing skeletal muscles, elastic fibres in the connective tissues of the body wall, and the parenchyma of the lung itself. When the inspiratory muscles relax, these elastic components recoil returning the diaphragm, the rib cage, or both to their original positions. This is known as elastic rebound. It has been shown that extensive rowing training reduces the elasticity of the inspiratory muscles, and the elasticity of the lung (Biersteker, et al., 1986). The decrease in elastic recoil that occurs in 4 years of competitive rowing is the equivalent to 27 years of the normal ageing process (Colebatch, et al., 1979). The aetiology and functional significance (if any) of the increase in compliance in response to rowing is unknown.

During diaphragmatic breathing, or deep breathing, contractions of the diaphragm provide the necessary change in thoracic volume. Air is drawn into the lungs as the diaphragm contracts and is pushed out when it relaxes. During costal breathing, or shallow breathing, the thoracic volume changes due to the shape of the rib cage. Contractions of the external intercostals elevate the ribs, and therefore enlarge the thoracic cavity (Martini, 1998).

As the level of activity increases and the amount of air required during breathing increases, the external intercostals increase in their relative contribution. However, even at rest, costal breathing can predominate when abdominal problems restrict diaphragmatic movements, as is the case in pregnancy (Martini, 1998). Forced breathing, or hyperpnoea, involves active inspiratory and expiratory movements. Forced breathing calls upon the accessory muscles to assist with inspiration, where expiration calls upon the internal intercostals to assist. At maximal activity, when the respiratory muscles are being used maximally (but also at lower intensities), the abdominal muscles are used in expiration. Their contraction compresses the abdominal contents, pushing them up against the diaphragm. This reduces the volume of the thoracic cavity. The role of the respiratory muscles in postural control and trunk stabilisation is considered in Section 2.7.

2.4 Lung Function Testing

During the last three decades, lung function tests have evolved from tools for physiologic study to clinical tools widely used for assessment of respiratory status. In addition to their use in clinical case management, they have become a part of routine health examinations in respiratory, occupational, sports medicine and public health screening (ATS, 1991).

2.4.1 Pulmonary Function Assessment

Routine measurements of respiratory function (volumes, flows, indices of gas exchange, etc...) are non-specific in relation to any medical diagnosis, but can give information regarding the performance of the respiratory muscles (Gibson, et al., 2002). Routine lung function tests look for evidence of airway dysfunction, such as asthma, but decrements in functions observed in this testing could also be indicative of respiratory muscle dysfunction (Gibson, et al., 2002).

Testing static lung volumes is one method of assessing overall respiratory function. The most frequently noted abnormality in lung volumes in individuals with respiratory muscle weakness or fatigue is a reduction in vital capacity (VC). This is the maximum amount of air that can be moved into or out of the lungs during a single respiratory cycle, which can be a force (FVC) or slow manoeuvre. FVC can be measured during inspiratory (FIVC; Figure 5a) or expiratory (FEVC; Figure 5b) manoeuvres. However, the pattern of these abnormalities is less consistent, as residual volume (RV; the amount of air remaining in the lungs after maximal expiration) is usually normal or increased.

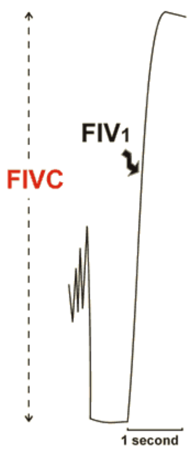

Figure 5a. Forced Inspiratory Vital Capacity (FIVC)

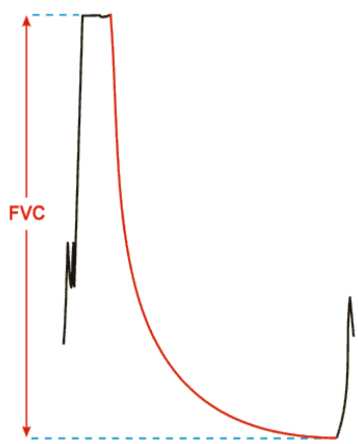

Figure 5b. Forced Expiratory Vital Capacity (FEVC)

However, total lung capacity (TLC) is less noticeably reduced than VC (the 'working' lung volume), with the RV/TLC ratio often increasing without implying airway obstruction (Gibson, et al., 2002). The VC can be limited by weakness of both the inspiratory and expiratory muscles, preventing full inflation and full expiration of the lungs. There have been a number of studies documenting decreased forced vital capacity after marathon running (Loke, et al., 1982; Warren, et al., 1989), and the most likely explanation for this observation is that maximal lung volume excursion is impaired due to respiratory muscle fatigue. A limitation of VC testing for the assessment of respiratory muscle weakness is that it is less sensitive than the direct measurement of maximal respiratory pressures. However, in contrast to maximal respiratory pressures, VC has excellent standardisation and well established reference values. The test is also easily performed, widely available and economical, but unfortunately has limited utility for testing elite athletes if the primary interest is respiratory muscle function.

Another method of testing lung volumes is to perform a maximum flow volume loop (MFVL). This test involves using a flow-volume analyser (e.g., the MicroLab, Micro Medical Ltd, Rochester). The participant inhales maximally, places their mouth over a cardboard tube connected to the analyser, and then expires maximally until residual volume is reached. Once this is obtained, the participant then inhales maximally until the lungs are again full. A typical flow volume loop resulting from this test on a piece of test equipment such as the MicroLab would look similar to that shown in Figure 5c.

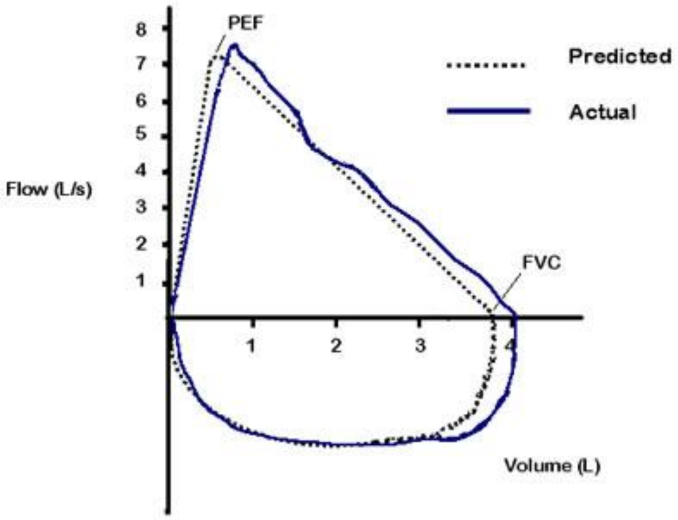

Figure 5c. A typical Maximal Flow Volume Loop (MFVL) showing
Peak Expiratory Flow (PEF) and Forced [Expiratory] Vital Capacity (FVC)

To determine respiratory muscle dysfunction or weakness, the maximum expiratory and maximum inspiratory flow volume curves characteristically show a reduction in those flows that are most effort dependent; they are peak expiratory flow at large lung volumes and maximum inspiratory flow at all lung volumes (Gibson, et al., 1979; cited in Gibson, et al., 2002). Maximum voluntary ventilation (MVV) was formerly recommended as a test for muscle weakness rather than volume, but the proportionate reduction is usually similar to that of VC (Braun, et al., 1983; cited in Gibson, et al., 2002). Additionally, and similarly to results found for FVC, reductions of MVV have been found after marathon running (Chevrolet, et al., 1993). The MVV test involves breathing maximally, either into a form of gas collection device (e.g. Douglas Bag) or using an ‘online’ gas analyser for a given period of time, usually 15 seconds. The volume of air that has been expired is measured or calculated and compared to reference data. Two disadvantages to this test are that it can become fatiguing if the test is carried out for a long period of time, and the test is highly effort and motivation dependant.

2.4.2 Measuring Respiratory Muscle Pressures

Muscles have two functions: to develop force and to shorten (Green, et al., 2002). In the respiratory system, force is usually estimated as pressure and shortening as lung volume change or displacement of chest wall features. Thus, quantitative characterisation of the respiratory muscles has usually relied upon measurements of volume, displacements, pressures and the rates of change of these variables. The relationship between pressure and force is complex. For example, the geometry of the lungs and the thoracic cavity plays a large role in the efficiency of the conversion of force into pressure (Green, et al., 2002). The thoracic cavity depends upon the mechanical properties of the rib cage and the abdominal wall, both of which interact with the respiratory muscles. A stiffer rib cage is better at resisting distortion, and therefore allows a greater amount of pressure to be produced by the diaphragm for a given level of force (Chihara, et al., 1996). In this instance, pressures created by the respiratory system should be viewed in terms of a global respiratory output. To test properties of the respiratory muscle, pressures can be measured during either voluntary or involuntary manoeuvres (whereby contraction is stimulated electrically or magnetically). For the former option, the action of several inspiratory or expiratory muscles is assessed, but for the latter, the pressure developed is specific to the contracting muscle or muscle group. (Green, et al., 2002).

2.4.2.1 Invasive Methods of Measuring Internal Pressures

Balloon catheter systems are the most widely used method for recording oesophageal pressures (P_{oes}) as a reflection of pleural pressure (P_{pl}), and gastric pressure (P_{ga}) as a reflection of abdominal pressure (P_{ab}; Milic-Emili, et al., 1964) Latex balloons containing air are sealed over catheters, which in turn transmit pressures to transducers. When choosing and preparing balloon catheter systems, care must be taken over the physical characteristics. Balloon volume, volume-pressure characteristics and catheter dimensions can all influence the measurements and introduce errors. Accordingly, standardisation has been proposed (Yernault, 1983; cited in Green, et al., 2002).

Fluid filled catheters have also been employed, mainly for use in studies of respiratory mechanics in small animals (Green, et al., 2002). The advantage of these is that the transmission of pressure using a non-compressible fluid gives a high frequency response. Additionally, the catheters can be smaller and thinner than for balloon catheters, and theoretically reducing discomfort. One disadvantage to using a liquid filled catheter is that pressure is always measured at the tip of the catheter, which may not always be the optimal site (Green, et al., 2002). However, studies of respiratory muscle pressures using these catheters in humans are limited.

Catheter mounted micro-transducers (which can be referred to as Millar catheters; Millar & Baker, 1973; cited in Green, et al., 2002), have a level of performance similar to that of the balloon catheters (Gilbert, et al., 1979). The management of these catheters during long studies is probably easier, as they come with a lower risk of technical problems, and like the liquid filled catheters are smaller than balloon catheters, which may make them more tolerable for the user. Their frequency response is high, which may eliminate phase lag sometimes seen with balloon catheters (Green, et al., 2002). However, currently these catheters only record pressure at a single focused point so that P_{es} pressures may not be as reflective of P_{pl} as balloon catheters may be. They are also more expensive than other forms of catheters, and confidence with sterilisation may become an issue.

Other systems are available, such as the use of fibre optic sensors. These have been used in measurements of cerebral pressures in neurosurgery (Wald, et al., 1977). It has been suggested that they may be useful for measuring respiratory pressures (Koska, et al., 1994), and may include advantages over other devices such as decreased chances of false measurement due to blockages through water or mucus, less chance of kinking, and possibly a faster response to pressure changes. However, all this remains to be established as no published studies on humans exist (Green, et al., 2002).

2.4.2.2 Non-invasive Methods of Measuring Internal Pressures

Mouth pressure (P_{mo}) is easy to measure, and changes give a reasonable indication of change in alveolar pressure, and therefore P_{es} (Green, et al., 2002), assuming there is relatively little pressure loss down the airways or across the lungs. This may be realistic with healthy lungs, particularly when changes in lung volume are small, but this may not be appropriate in individuals with lung or airway disease (Green, et al., 2002). Mouth pressure may also be used as an indication of diaphragmatic pressure (P_{di}) when the diaphragm is contracted involuntarily against a closed airway (Green, et al., 2002). Mouth pressure is measured via a side port of a mouthpiece, although this mouthpiece should be easily fitting for the participant to close their mouth around, and should incorporate a small leak to prevent glottic closure during inspiratory or expiratory manoeuvres (Black & Hyatt, 1969). The type of mouthpiece should be standardised, as this can significantly influence the results, especially for expiratory pressures (Koulouris, et al., 1988).

Volitional tests for inspiratory and expiratory muscle strength are most commonly performed, as they are simple and well tolerated by users (Green, et al., 2002). All measurements are taken via external equipment, therefore there is no need for catheter insertion. However, it is difficult to determine if the participant is making a truly maximal effort. Although generally most people can maximally recruit peripheral and respiratory muscles during voluntary efforts (Gandevia & McKenzie, 1985), it has been argued that even experienced physiologists rarely produce reliable efforts (Bigland-Ritchie, et al., 1992; cited in Green, et al., 2002). As a result, it can be difficult to determine whether a low reading represents reduced respiratory strength or a ‘poor’ effort. Equally, it might be argued that the inability to fully activate one’s muscles has functional relevance, particularly as there is evidence that there may be central, possibly reciprocal, inhibition of locomotor and respiratory motor output (Verin, et al., 2004).

Measurements of maximum static inspiratory pressure (MIP) or maximum static expiratory pressure (MEP) that a participant can generate at the mouth are simple ways to gauge inspiratory or expiratory muscle strength. The pressures developed during these manoeuvres reflect the pressures developed by the respiratory muscles (P_{mus}), and the passive elastic recoil pressure of the respiratory system (P_{rs}) including the lungs and chest wall (Green, et al., 2002).

An advantage of using P_{mo} is the simplicity and ease of use. Reliability of the technique is high, especially in athletic individuals (Romer & McConnell, 2004), and results in

MIP and MEP are sensitive to changes induced by fatigue and training regimens. The tests are uncomplicated to perform and are well tolerated by participants. The recent developments of hand-held mouth pressure meters (e.g. MPM, Micro Medical Ltd, Rochester) have made portable measurements even easier. However, a number of major disadvantages exist. The investigator cannot discriminate between weaknesses of the different respiratory muscles, as muscle recruitment with this method is global. Additionally, the tests are volitional, and require full cooperation, which requires high levels of motivation. Another problem exists in the interpretation of the measurements and with definitions of “weakness”, since MIP and MEP are not related to any index of body size or other physical characteristic. Notwithstanding these limitations, in motivated subjects, MIP and MEP provide meaningful indices of changes in intra-individual function.

2.5 Locomotor-Respiratory Coupling

Locomotor-respiratory coupling (LRC), or entrainment, is the synchronising of the movements of the body during an exercise modality and breathing rhythms. Entrainment of respiration with locomotion has been observed in various rhythmic activities including walking, running, cycling, swimming and rowing (Bechbache & Duffin, 1977; Bramble & Carrier, 1983; Garlando, et al., 1985; Hill, et al., 1988; Jasinkas, et al., 1980; Kay, et al., 1975; Kohl, et al., 1981; Paterson, et al., 1986; Siegmund, et al., 1999; Bonsignore, et al., 1998; Mahler, et al., 1991a). It has been suggested that LRC may limit the mechanical interference exerted by the active muscles used in ventilation (Bonsignore, et al., 1998), however, it is reasonable to suggest that the mechanics of the rowing stroke may limit the individuals’ ability to perform LRC.

The entrainment of breathing in humans seems quite varied, with influences from a number of factors, such as the type of exercise (Bechbache & Duffin, 1977), the degree of fitness (Bernasconi, et al., 1995), and the presence of visual or acoustic stimuli to maintain rhythm of exercise (Bechbache & Duffin, 1977). Additionally, differing methods of analysis (Kay, et al., 1975), as well as volitional aspects such as prior information regarding the purpose of the study (Paterson, et al., 1986) also have an effect. In addition to studies concerning the physiology of the control of entrainment, LRC has also been studied during sport specific activities with reference to training and performance (Clark, et al., 1983; Mahler, et al., 1991a; Steinacker, et al., 1993).

The respiratory system has not traditionally been thought to limit exercise performance at sea level. However, due to the large muscle recruitment involved in rowing, the demand for oxygen is much higher than for many other endurance sports. As mentioned before, the high oxygen demands of rowing may push the ability of the respiratory pump to meet the associated ventilatory demand close to its mechanical limit, especially with maximal ventilation rates exceeding 200 $l.min^{-1}$ (Hagerman, et al., 1978; McKenzie & Rhodes, 1982). Although intermediate and elite level oarsmen have comparable levels of forced vital capacity (FVC) and forced expiratory volume in 1 second ($FEV_{1.0}$), there are differences in how these functions are utilised. Elite rowers tend to have higher tidal volumes (V_T) and lower breathing frequencies (f_B) than untrained rowers during incremental tests to the limit of tolerance (Mahler, et al., 1991b). Whether all rowers manage to achieve very high ventilation rates is questionable, but it could well be advantageous to do so, as it has been shown that elite rowers do have superior lung function when compared to novice rowers (Faulman, et al., 1996; Donnelly, et al., 1991). This suggests that either the training involved in rowing improves various ventilatory parameters (maximum expiratory flow at 50% forced vital capacity (FVC; $MEF_{50\%FVC}$), maximum expiratory flow at 25% FVC ($MEF_{25\%FVC}$), total lung capacity (TLC), functional residual capacity (FRC), residual volume (RV), peak inspiratory pressure at residual volume (Pi_{RV}) and peak expiratory pressure at total lung capacity (TLC; Pe_{TLC}); Donnelly, et al., 1991), or that elite rowers are genetically predisposed to have superior lung function. The former is very unlikely, since the lungs appear to be remarkably unresponsive to physical training (Wagner, 2005).

A unique aspect of the action of the respiratory muscles in rowing is that they contribute to the generation of force during the stroke, as well as for ventilation (Biersteker, et al., 1986; Mahler, et al., 1991b). Indeed, rowers may elect to couple breathing with stroke movements in order to improve performance (Maclennan, et al., 1994). Many entrainment studies have been conducted in rowing (Siegmund, et al., 1999; Mahler, et al., 1991a; Mahler, et al., 1991b; Maclennan, et al., 1994; Steinacker, et al., 1993). Entrainment has been found to occur in ratios of breaths per stroke ranging from 1:1 right up to 3:1, the most common ratio being 2:1 (Siegmund, et al., 1999; Mahler, et al., 1991a). Szal & Schoene (1989) found a ratio of 2:3 at maximal effort, and subsequently concluded that ventilation could not be synchronous with the rowing stroke. Besides showing a range of frequency relations, athletes also show transitions between these ratios (Bramble & Carrier, 1983) at different power outputs.

To date, assessments of entrainment in rowers have mostly been conducted using incremental exercise and not during race simulations; the rowers' goal for these two tests is completely different. During a maximal 2,000 m effort on an ergometer, the goal is to minimise the time taken to complete the distance (whilst remaining synchronised with the other team mates in the crew if applicable). In contrast, the goal of an incremental test is to maintain a specific power output, and the power output for a higher increment is often achieved by increasing stroke rate (Steinacker, et al., 1993). However, it has been shown that there are no significant differences between maximal physiological variables between these two types of test (Mahler, et al., 1984). One study that has assessed entrainment during a 2,000 m maximal effort Siegmund, et al. (1999) found that eight of eleven (73%) varsity rowers entrained ventilation for periods of at least 120 seconds during the test, although, 1) no stable entrainment patterns were observed and, 2) there were no reported decrements in oxygen consumption during these parts of the test; thus, entrainment did not appear to result in any measurable decrease in the oxygen cost of rowing.

In contrast, it has been shown that entrainment induced by paced breathing decreased oxygen consumption by a small, but statistically significant amount in cycling (Garlando, et al., 1985) and running (Bernasconi, et al., 1995). As mentioned previously, it has also been shown that respiratory musculature during strenuous exercise can command approximately 16% of the total oxygen consumption in highly trained athletes (Harms, 2000). An explanation for the decreased oxygen consumption in both running and cycling may arise from the fact that they are predominantly lower limb activities, with little or no requirement for the upper body to produce force. Although power during rowing is predominantly generated by the lower limbs, the respiratory muscles of the torso are involved in force production and for the transmission of force through the body (Biersteker, et al., 1986; Mahler, et al., 1991b). This additional function may obscure the oxygen cost benefits of entrainment that are observed in running or cycling. Another possible explanation is that, in a complex motor task such as rowing, the effects of entrainment may take months, or even years, to perfect before a measurable improvement is manifest. This possibility was considered by Mahler, et al. (1991a), who found that entrainment could develop in novice rowers after an 8-month training program; however they reported no reduction in oxygen consumption. Furthermore, there have not been any studies published to date showing that spontaneous entrainment of breathing actually affects oxygen consumption during exercise.

A recent study by Daffertshofer and colleagues (2004) suggests that a single physiological, albeit mechanically constrained, quantity sufficed to explain the observed entrainment phenomena, viz., the effective oxygen volume in the lungs. This study further suggested that the cyclic abdominal pressure swings (found by Manning, et al., 2000) modulate the self-sustaining rhythm of respiration, modify total lung pressure, and cause local maximal energy transfer at frequency ratios between movement and respiration that are composed of small integers. Daffertshofer et al. (2004) concluded that optimising the effective oxygen volume in the lungs could be seen as the mechanism that drives respiration to synchronise with locomotion, but provided no information regarding the potential effect of this upon the economy of rowing.

Siegmund, et al. (1999) found that there were two dominant ventilatory strategies used by rowers to maintain entrainment. The first strategy consisted of adjusting both ventilation rates and expired volumes. Inspired volumes remained relatively stable over the last two-thirds of the 2,000 m effort, whereas expired volumes fluctuated between small volumes during the recovery (leaving a greater volume in the lungs at the catch), and large volumes (leaving a smaller volume in the lungs at the finish) during the drive (Figure 6). This strategy affects the volume of the lungs throughout the drive phases of the 2,000 m effort. The results of the Siegmund study have relevance to that performed by Manning, et al. (2000). Manning et al. suggested that the differences in lung volume at the catch potentially affect intra-abdominal pressure (IAP), which in turn could have an effect upon spinal stability, but it may also influence force transmission through the body and potentially force production through the oar. This hypothesis is discussed in greater depth later in this section.

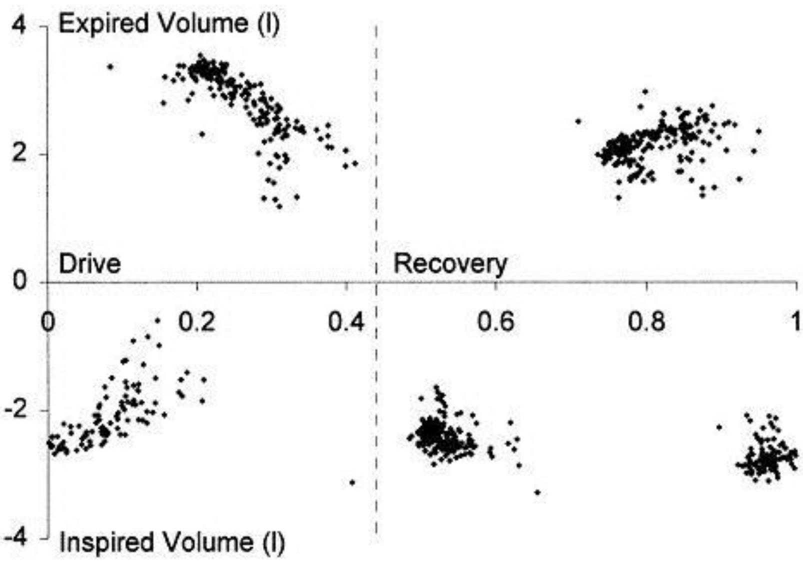

Figure 6. Absolute expired and inspired volumes vs. normalised stroke.
Taken from a subject who entrained their breathing at a ratio of 2:1

To achieve an alternating pattern of expired volume, the rowing must employ short-duration breaths during recovery and long-duration breaths during the drive. In the study of Siegmund, et al. (1999) this pattern was achieved whilst maintaining similar peak flow rates during drive and recovery. The second strategy used by their subjects resulted in a less distinct alternating pattern of expiratory volumes, but with maintenance of a regular instantaneous ventilatory rate, and alternating between high peak expiratory flow rates during the drive and low peak expiratory flow rates during recovery.

Given the consistency of locomotor output during the rowing stroke, and the differing ventilatory strategies used to maintain entrainment, it appears that rowers alter breathing pattern to match locomotion under race conditions. However, despite increasing demands to breathe during various tests, rowers generally maintain stroke rate and power output (Siegmund, et al., 1999). It has been speculated that the ability to couple respiration with the mechanics of the rowing stroke may be due to the effects of training (Mahler, et al., 1991b), genetic factors (Mahler, et al., 1991b; Mahler, personal communication), or, more recently, to inherent behaviour of the neural network within the respiratory system (Del Negro, et al., 2002a; Del Negro, et al., 2002b; both cited in Daffertshofer, et al., 2004). However, it seems more likely that entrainment and its potential benefits may only become noticeable after a considerable amount of time spent developing entrainment during rowing, as hypothesised in the Mahler study (Mahler, et al., 1991a). However, no longitudinal studies have yet been published to confirm whether or not this is the case.

There are other factors involved in LRC that could potentially affect performance that are not assessed in the context of a time trial, 1) synchrony between respiratory and locomotive systems are likely to increase the mechanical efficiency of ventilatory and locomotive activities, and therefore decrease the overall metabolic cost of locomotion (mentioned above), and 2) the coordination of breathing and locomotion rhythms has been suggested to alleviate some respiratory discomfort associated with exercise (Banzett, et al., 1992; Bernasconi, et al., 1995). A number of studies have addressed this second assumption. Both Maclennan, et al. (1994) and Takano & Deguchi (1997) investigated the sensation of breathlessness and respiratory oxygen cost during exercise with conscious entrainment of breathing. However, neither of these studies found that entrainment of breathing significantly reduced the oxygen cost of work (as found in other sports), or reduce the sensation of breathlessness.

Takano & Deguchi (1997) discovered wide variations in the differences of physiological measurements ($\Delta \dot{V}O_2$, $\Delta \dot{V}_E$, oxygen uptake of the respiratory muscles $\Delta \dot{V}O_{2RM}$) among subjects between entrained and non-entrained exercise runs. The authors then went on to suggest that their results indicated that reductions in total $\dot{V}O_2$ and sensation of breathlessness with entrainment could occur in subjects who displayed a reduction in $\dot{V}O_{2RM}$ during entrained runs. Maclennan, et al. (1994) used different protocol and different test measures to the Takano and Deguchi study, and although comparison was performed between the entrained runs of the two studies, they used differing breathing protocols, thus comparisons between the two studies in terms of their results is difficult. However, Maclennan, et al. (1994) did suggest (as several other authors on this subject have) that the physiological and perceptual benefits of LRC may require months, if not years, of training to achieve.

Despite the many empirical findings in the numerous studies that have taken place, the mechanisms underlying entrainment, and the functional implications of entrainment for performance, are far from understood.

2.6 Posture, Lung Volume, Force Production & The Spine

The rowing stroke and the positions of the athlete's body during the rowing stroke were described in earlier sections. During each rowing stroke, various forces act upon the rib cage and the diaphragm, with consequent pressures transmitted to the thoracic cavity. At the beginning of the drive (i.e. when the knees and hips are flexed, torso and arms extended), the visceral mass compresses the abdominally apposed lung volume (Daffertshofer, et al., 2004). This compression vanishes when the legs have extended, but returns at the final part of the drive when the abdominal muscles become active in supporting the torso at the finish (Daffertshofer, et al., 2004). This muscle-activity-induced compression again disappears during mid-recovery, only to become active again at the catch. Thus, during a single rowing stroke, the lungs are mechanically compressed twice and diaphragm movement impeded (Wasjwelner, et al., 2000 – cited in Daffertshofer, et al., 2004; Rodriguez, et al., 1990). Trunk movements in well-trained rowers range from 30^o of flexion at the catch to 28^o of extension at the finish (Hosea, et al., 1989), which aids the understanding of the position of the body in these two positions.

Intra-abdominal pressure (IAP) also peaks twice during a rowing stroke (Manning, et al., 2000). The points at which maximal IAP and 'natural' mechanical lung compression occur do coincide, although only at the finish position do they also coincide with expiration (Mahler, et al. 1991a). The term 'natural' mechanical compression is used as there are other compressive forces acting upon the rib cage through the act of rowing; during the drive, the forces acting upon the rib cage via the arms, shoulders and upper torso transferring force through the oar will compress the rib cage. 'Natural' mechanical compression is most prominent at the catch and finish positions when the position of the body acts as a compressive force on itself without the influence of an external movement, such as transferring force through the body to an oar.

Siegmund and colleagues (1999) recorded ergometer handle force during rowing. Entrainment was assessed in terms of the ratio between the averages over consecutive 10 s intervals of instantaneous ventilation versus instantaneous stroke rate, and subsequently observed stroke rate and breathing synchrony at various ratios. However, the synchronisation between handle forces and breathing rhythms observed by Siegmund, et al. (1999) did not reflect the synchronisation between lung pressure oscillations and respiration (Daffertshofer, et al., 2004). This could have implications for the theorised benefits of entrainment and the stability of the spine during the drive (Manning, et al., 2000). When the lungs are mechanically compressed, expiration occurs as the pressure within the lungs increases. As only one of the points of mechanical lung compression coincides with expiration (the finish; Mahler, et al., 1991a), it would be logical to expect that additional respiratory effort would be needed to overcome the compressive forces acting on the lung at the catch in order to inhale sufficiently. It may be beneficial to entrainment and the economy of rowing to adapt the rhythm of breathing to expire at the times when the lungs are mechanically compressed. Expiration would occur during mechanical compression (i.e. at the catch and finish positions), and inspiration to be performed when the lungs are not under the influence of mechanical compression (i.e. mid-drive and mid-recovery). This could potentially decrease the oxygen cost of breathing, as expiration and inspiration would be assisted through natural compression and expansion of the lungs. However, inspiration during the drive of the rowing stroke could compromise IAP and spine stability (Manning, et al., 2000), which in turn could potentially affect force transference through the drive. Additionally, breathing in during a physical effort, such as lifting or pulling on an oar, is counter-intuitive, and may not be very easy to implement. This concept of exploiting the natural expansion and compression of the respiratory structures needs further investigation to establish its merit.

It was argued in the mid 1970's that the position of the body at the catch placed the body in a cramped position (Cunningham, et al., 1975). The Cunningham group also speculated that the cramped position increased the intra-abdominal pressure (IAP), which was later confirmed directly by Manning, et al. (2000). Manning, et al. (2000) also found that IAP increased significantly as work rate increased, which confirmed earlier work by Norris (1995), who suggested that the magnitude of IAP was dependent upon the load placed upon the spine; the greater the load, the stronger the contraction of the abdominal muscles, and the greater the IAP. During the drive phase of the rowing stroke, the lower lumbar vertebrae of rowers can be subjected to shear loads of up to 850 Newtons (850 N) and compressive loads of up to 6000 N (Hosea, et al., 1989), and although there is not a high prevalence of injuries in rowing (Budgett & Fuller, 1989), a large proportion of rowing injuries are spinal (Stallard, 1995; Strayer, 1990 – cited in Manning, et al., 2000; Hosea, et al., 1989). The increased IAP in the catch position may impair downward excursion of the diaphragm, and therefore inspiration, but research has suggested that a high IAP may protect the spine from the detrimental effects of high levels of shear and compressive forces (Norris, 1995; McGill & Norman, 1987; Marras, et al., 1985). Additionally, Al-Bilbeisi & McCool (2000) discovered that the diaphragm undergoes involuntary static contraction during lifting type manoeuvres, which the rowing stroke is similar to. This could impede an individual's ability to inhale. It seems that there may be opposing requirements for effective ventilation and protection of the spine that require further investigation.

Siegmund, et al. (1999) recorded values for peak flow rates and maximal expired volumes in various body positions. Significant differences were found between the values for maximal expired volume in a normal sitting position (similar to that found at the finish of the stroke) and the maximal expired volume at the catch. Expired volumes were significantly lower in the catch position than standing or sitting volumes (Siegmund, et al., 1999), although the peak flow rates were not significantly different. This suggests that the ability to generate changes in lung volume may be impaired at the catch, but the flow generating capacity is not.

A study undertaken by Beck, et al. (1998) examined the effects of lung volume upon EMG signal strength of the diaphragm during voluntary contractions at different lung volumes. They found that there was a direct relationship between the EMG signal strength of the diaphragm and trans-diaphragmatic pressure, independent of diaphragm length. This information confirms that at differing lung volumes, the level of activation of different respiratory muscles varies (the focus of the Beck study being the diaphragm). The data from the study performed by Beck, et al., (1998) also suggested that as lung volume increased, the magnitude of the motor drive to the diaphragm at any given trans-diaphragmatic pressure also increased. This means that in its stabilising role, the diaphragm is working at greater percentages of it maximum capacity to generate force as lung volume increases. As mentioned previously, a secondary role of some of the muscles used in respiration is to stabilise the trunk, and the contribution of these muscles to stabilisation of the spine may be compromised by their role in respiration

(Hodges, et al., 1997a). The diaphragm has been shown to play a part in postural stability during sudden and rapid movements of the upper limbs (Hodges, et al., 1997b), such as those found in rowing (moving the arms at the onset of recovery). The established role of the diaphragm in providing adequate ventilation may compromise its ability to provide postural control, potentially affecting entrainment and inspiratory muscle fatigue.

Stiffness of the spine is affected by many factors, including muscle activity and associated stiffness of the muscles and other surrounding soft tissues (Lee, et al., 1996; cited in Shirley, et al., 2003). The effect of paraspinal muscle activity on stiffness has been investigated extensively (Cholewicki, et al., 1999; cited in Shirley, et al., 2003) and activity of erector spinae of 10% MVC increases spinal stiffness by 12% (Shirley, et al., 1999; cited in Shirley, et al., 2003). The cyclical variation of paraspinal activity that occurs during respiration may affect spinal stiffness during the respiratory cycle (Hodges, et al., 2002 cited in Shirley, et al., 2003). Activity of the diaphragm, paraspinal muscles, abdominal muscles and IAP are modulated differently across the respiratory cycle. During eupnoea, diaphragm activity is greatest during inspiration, and is associated with elevated IAP (Campbell & Green, 1953; cited in Shirley, et al., 2003). Activity of the paraspinal and abdominal muscles varies between individuals and postures (Hodges, et al., 2002 - cited in Shirley, et al., 2003; De Troyer, et al., 1990; Hodges, et al., 1997a). When expiratory volume or flow is increased, activity of the abdominal (Goldman, et al., 1987) and paraspinal muscles is increased and is associated with increased IAP (Campbell & Green, 1953; cited in Shirley, et al., 2003). As a result of the complex interaction between muscle activation and IAP with respiration, it is uncertain whether or how the stiffness of the spine varies across the respiratory cycle.

Shirley et al. (2003) shed some light on the subject in a study showing that stiffness in the lumbar spine (L_4 and L_2 vertebrae) increased above baseline levels at functional residual capacity with both inspiratory and expiratory efforts. Increase in stiffness was related to respiratory effort, and was greatest at maximum expiration (Shirley, et al., 2003). This suggests that changes in trunk muscle activity with respiratory efforts are important in the modulation of spinal stiffness.

The trunk muscles play an important role in spinal stabilisation, preventing ‘buckling’ under pressure during various force-producing tasks (Gardner-Morse, et al., 1995). They also contract to stabilise the thorax and abdomen, allowing upper-body weight to be transferred through the pelvis (Bartelink, 1957). Additionally, the abdominal wall muscles are activated to assist in the movement of airflow into and out of the thorax and to assist breath-holding in lifting (Creswell & Thorstensson, 1994). The role of the abdominal muscles in postural control is complicated by their contribution to breathing (Hodges, et al., 1997a), as has been found in other muscles such as the external obliques (De Troyer, et al., 1990), and the transversus abdominis (Kang & Lee, 2002).

The abdominal musculature has been examined in its relationship to expiration during incremental exercise to the limit of tolerance and constant work rate cycling exercise (Abraham, et al., 2002). The respiratory related activation of the external obliques was evoked in four of seven subjects, and rectus abdominis evoked in six of seven subjects. Although abdominal muscles are rarely recorded using EMG during quiet breathing, they are activated towards the end of expiration in conditions were ventilation is increased (Goldman, et al., 1987). Expiratory activity of both external obliques and rectus abdominis increased with exercise intensity; peak values averaged 10-20%

(external obliques) and 20-40% (rectus abdominis) of peak muscle activity (Abraham, et al., 2002). The authors also found that during exercise at a constant work rate, EMG activity increased to 40-50% (rectus) and 5-10% (ex. oblique) of peak, and then plateaued at this level, despite a continual increase in oxygen uptake and minute ventilation. This study suggests that the abdominal muscles play a role in regulating the ventilatory response to progressive intensity cycle exercise as well as spinal stability, although some of their observed activity probably supports postural adjustments or limb movements (Abraham, et al., 2002).

McGill, et al. (1995) investigated the loads placed on the lower back during lifting with elevated ventilation. They found that the muscular activation during a certain lifting task was affected not only by the muscular forces required for the lifting task and maintenance of spinal stability, but also by the ways in which the subject breathed during the lifting; whether by inspiring, expiring or breath-holding (McGill, et al., 1995). Although a rower would not typically be lifting anything during a rowing stroke, the stroke has been likened to performing a deadlift from the catch position (Banks, personal communication) in order to propel the boat through the water, or to drive against ergometer resistance. This highlights the importance of clarifying relationships between ventilation during lifting (or driving during the rowing stroke) and the consequent muscular activation, as this affects intra-abdominal pressure and spinal stability (Manning, et al., 2000), spinal loading (Kang & Lee, 2002), and possibly maximal force production.

In many lifting-type activities, it is common for inspiration to occur and for this inspiration to be held, especially if the load is particularly heavy (Kang & Lee, 2002).

When this glottis is closed, this is known as the Valsalva manoeuvre, however, if the glottis remains open, it is known merely as breath holding. There is much debate about the effect of the Valsalva/breath-holding manoeuvres upon trunk muscle activation. Some studies have found increased muscular activation whilst using the Valsalva manoeuvre (Nachemson, et al., 1986; Cholewicki, et al., 1999), whilst other studies have found less activation when compared to continuous expiration (McGill, et al., 1990). The differences between these findings could be due to other factors related to breath-holding, such as lung volume and the duration of the hold, which could influence trunk muscle activities (Kang & Lee, 2002).

Using the squat manoeuvre, Kang & Lee (2002) studied the effects of manual lifting with spontaneous ventilation and breath holding (without glottis closure) upon trunk EMG. Of the four muscles measured in the study (rectus abdominis, erector spinae, abdominal external oblique and latissimus dorsi), only the external obliques were affected by breathing manoeuvres, up to 5% of MVC. Kang & Lee (2002) also concluded that glottis closure, as well as a sustained intrathoracic air volume, affected trunk muscle activity during lifting, confirming results from previous investigations by Hodges, et al. (1997a). Additionally, Kang & Lee (2002) found that lifting at residual volume (RV) resulted in higher activation of the external oblique muscles during pre-lifting than lifting at a lung volume above RV. In contrast, when two breathing manoeuvres (breath-holding *vs*. non-holding) were compared with similar air volume inside the thoracic cavity, sustained breath holding resulted in a higher external oblique activation than non-holding, during which a significant increase in diaphragmatic activation was reported (Kang & Lee, 2002). To optimise the stability of the spine, it has been suggested that there must be a trade-off (Granata & Marras, 2000) between the positive effects of increasing trunk stiffness (McGill, et al., 1995; Gardner-Morse & Strokes, 1998), and the possible negative effects of increasing compressive loads (Granata & Marras, 1995). It is clear from the Kang & Lee (2002) study that breathing and breath holding have potentially important effects upon the activity of muscles that are important for trunk stabilisation, force transfer and spinal stabilisation.

The population prevalence of back injuries amongst rowers varies quite widely from one study to another. Hagerman (1984) reported results of chronic lower back pain in only 2.8% (26 of 931) of his study population. Of these back injuries, more than half led to a loss of less than one week of training, and six cases were necessary for the athlete to withdraw from rowing for an entire season. In contrast, Howell (1984) found lower back pain in 82% of lightweight female rowers, compared to 20-30% of the general population. However, it is difficult to compare these percentages, as Howell (1984) did not state the severity of injury in as much detail as Hagerman did in his 1984 study. Boland and Hosea (1994) found chronic back problems in 21.7% (39 of 180) of university class rowers, which is a significantly higher percentage than that published by Hagerman (1984). Furthermore, Budget & Fuller (1989) recorded 13% of oarsmen reporting back injuries during on-water rowing, with an additional 21.7% complaining of injuries during land training. Back problems have increased during recent years (Shephard, 1998), possibly owing to longer slides and higher feet positioning in boats (Stallard, 1980), and the increasingly intense land training programs that are now undertaken (Shephard, 1998). It is clear from these reports of lower back injury that trunk respiratory muscle recruitment during rowing and trunk respiratory muscle training could have an effect upon the stability of the back and the prevalence of lower back injury in rowers. It is useful and interesting to note, that Roy, et al. (1990) have developed a technique for identifying susceptible individuals based on the changes in surface EMG induced by a fatiguing, high force contraction of the trunk musculature.

2.7 Respiratory Muscle Fatigue (RMF)

Exercise places heavy demands upon the respiratory muscles, and is a condition where the potential for respiratory muscle fatigue (RMF) exists. There have been many approaches to assessing this phenomenon, including measurement of maximal voluntary mouth pressures (Bye, et al., 1984; Hussain & Pardy, 1985; Loke, et al., 1982; Younes & Kivinen, 1984; Romer, 2002) electromyographic [EMG] power spectrums (Bye, et al., 1984; Hussain & Pardy, 1985) and trans-diaphragmatic pressures (Levine & Henson, 1988).

The role of RMF in exercise limitation in normal subjects is not fully understood, although it is thought that RMF does not constrain maximal aerobic power as determined by maximal incremental tests (Gallagher & Younes, 1989; Killian & Campbell, 1985 – cited in Marciniuk, et al., 1994; Younes & Kivinen, 1984), it is not so certain in the case of endurance exercise (submaximal exercise at a constant power output to exhaustion). In this case, the respiratory muscles do not work as intensely, but work for a significantly longer period of time. Studies have reported reductions in MIP and MEP after marathon running (Loke, et al., 1982) and reductions in maximal diaphragmatic pressure in normal subjects after fixed-intensity exercise to the limit of tolerance (80%$_{max}$; Bye, et al., 1984).

However, a study by Marciniuk, et al., (1994) found that central RMF played no role in affecting or determining ventilation, breathing patterns, sense of respiratory effort or exercise duration during constant intensity exercise to the limit of tolerance. It is interesting to note that the authors observed that inducing RMF before endurance exercise did not affect breathing patterns or ventilation of subsequent exercise performed on a cycle ergometer. It has since been argued that the pre-exercise intensity of the RMF in this study was too low to induce significant fatigue (Romer, personal communication). Some studies have shown otherwise (Mador & Acevedo, 1991). Mador & Acevedo (1991) performed a study where inspiratory muscle fatigue (IMF) was induced prior to exercise to the limit of tolerance at 90% maximal work capacity (W_{max}). IMF was achieved by inspiring against a load equivalent to 80% of maximal mouth pressure until the respective pressure could no longer be achieved. Mador & Acevedo (1991) found that after the induction of IMF, exercise time, oxygen consumption and heart rate were higher than during control. Minute ventilation and sensation of breathlessness were significantly higher, with alterations in the pattern of breathing. The latter may have a bearing on the ability to entrain locomotor activity with breathing, but further investigation of this phenomenon is required.

The majority of these types of studies have focused upon the fatiguing of inspiratory muscles, with only few looking at fatigue in expiratory muscles. One such study conducted by Kyroussis, et al., (1996) focused on abdominal muscle fatigue. The abdominal muscles are the primary muscles of active expiration, and as such facilitate subsequent inspiration (De Troyer, 1983). Fatigue of these muscles could not only impair ventilation, but could also affect spinal support, making the spine less efficient for force transmission and more prone to injury. Kyroussis, et al., (1996) found that after just 2 minutes of maximal ventilation, their measure of abdominal force (twitch gastric pressure) fell significantly (17%). More recently, Taylor, et al. (2006) also found significant abdominal fatigue after sustained high-intensity exercise. Fatigue of this magnitude after such a short period of maximal ventilation could have severe effects in rowing for spinal stability and force transmission, especially as maximal levels of ventilation during rowing can last longer than 2 minutes.

2.8 Summary

In a mechanically complex sport such as rowing, it is vital to understand the interaction of breathing and locomotion in order to optimise the influence of the trunk respiratory muscles upon force production and spinal stability. The high metabolic cost of rowing must also be borne in mind, since breathing must be simultaneously subservient to the requirement for adequate ventilation. Not until the interactions of these factors are understood can interventions be devised and recommendations made.

This study is being conducted in an attempt to clarify the relationship between different lung volumes at the catch to the force that is produced during the subsequent drive in a single rowing stroke. The first hypothesis is that as the volume of air within the lungs increases, force production at the catch will increase, thus, as the lung volume increases, the resulting trunk muscle activation should increase intra-abdominal pressure, and augment spinal stability. This should lead to greater transference and production of force in the rowing stroke. Further, a secondary hypothesis is that prior fatigue of the inspiratory muscles will impair force and power production in the catch position. These hypotheses are based upon information that has been laid out in this review.

Chapter 3: Methodology

3.1 Participants & Recruitment

Nine international standard competitive male rowers (8 heavyweight, 1 lightweight; mean [SD]; age 21.9 [9.0] years; stature 190.4 [5.2] cm; body mass 88.6 [10.8] kg; rowing training 5.6 [1.3] years; personal best 2,000 m ergometer time 369.3 [16.8] seconds; 88.4% world record time) took part in the investigation, which was given approval from the Institutional Ethics Committee. Measurements of athletes' stature were taken using a wall mounted stadiometer (CMS Equipment Ltd, London, UK), with weight being measured using electronic scales (Model 880, Seca, Birmingham, UK).

Recruitment of all of the athletes was through personal contact, in a group context. The respective coach/captain of each club/crew was contacted prior to any athletes being approached, and a meeting setup to inform them about the details of the investigation. Prior to any contact with the athletes, permission was sought from the coach/captain to allow their athletes to take part in the investigation. If consent was obtained, all of the athletes under the supervision of that coach were approached in the form of a group and asked for their verbal permission to be included in the study. All participants were given a verbal explanation as to the nature of the study, without indicating expected results, before any commitment from the athlete was gained. Once this had been achieved, the investigators maintained direct contact with the athletes regarding dates and times (in conjunction with their respective coach) for testing sessions to take place.

It was made clear to all volunteers that the option to withdraw from the study without the need for an explanation was available at any time. After verbal agreement was given, and study information (Appendix A) was read, the successful completion of a pre-test health screening questionnaire (Appendix B) and written informed consent form (Appendix C) was necessary to allow the athlete to participate in the study. All athletes were involved in training for the sport of rowing at the time of the study and were competing at either national or international level. Hence, all participants were competent users of the rowing ergometer used in this investigation, and at the time of testing all athletes were well into the training season and were well-trained for the time of year.

3.2 Study Design

To assess the influence of lung volume upon force production in rowing, and the effect of inspiratory muscle fatigue upon this influence, it was necessary to perform a number of measurements of lung function and power production at various lung volumes. To investigate the effect of inspiratory muscle fatigue, it was necessary to reproduce the lung function and power production tests after fatigue inducing sessions.

Prior to any testing, the athletes were prepared with a standardised warm-up. This consisted of whole body and respiratory manoeuvres. The following lung volumes were identified for assessment; total lung capacity (TLC), residual volume (RV, or $0\%_{TLC}$), and three volumes between RV and TLC ($25\%_{TLC}$, $50\%_{TLC}$, $75\%_{TLC}$). The subject's self-selected (SS) lung volume (the volume that was adopted spontaneously when asked to select their own lung volume) was also assessed. The lung volumes were achieved by inspiring to TLC, and with using feedback provided by the OxyCon metabolic cart, expiring a specified volume of air in order to achieve the required percentage TLC. In the case of RV, the lungs were emptied from TLC. This investigation utilised a semi-Valsalva manoeuvre during a single stroke drive, as breath holding during lifting has been shown to increase trunk muscle activation (Nachemson, et al., 1986; Cholewicki, et al., 1999; Kang & Lee, 2002). A number of baseline (non-fatigued) lung function measurements were taken prior to any testing, consisting of maximal inspiratory [mouth] pressures (MIP), maximal expiratory [mouth] pressures (MEP), and maximal flow volume loops (MFVL). MIP and MEP measurements were taken with a portable hand-held mouth-pressure-meter (MicroMPM, Micro Medical, Kent, UK), and MFVLs were taken using a portable spirometer (MicroLoop, Micro Medical, Kent, UK). MIPs at the testing lung volumes were also measured to determine a pressure-volume relationship for each individual. Once these baseline measures had been completed, non-fatigued measurements of rowing force and power production at each lung volume were assessed.

3.2.1 Visiting the Laboratory

One of two visits to the laboratory was used to complete the necessary health and consent forms, to introduce the athlete to the equipment being used in the investigation, to ascertain baseline measurements of the athlete’s lung function, and to perform some familiarising maximal strokes on the rowing ergometer. The opportunity was also taken for the athlete to become accustomed with the gas analysis equipment, and to practise attaining the desired lung volumes selected for the study.

A number of lung function measurements were made. Firstly, 5 MIPs were taken prior to the individual performing any of the lung function measures. Upon successful completion of valid measurements (valid MIP and MEP measurements require three values to be within 5cmH_2O of each other [ATS, 1991]), the respiratory warm-up was performed based on these MIP measures. The maximum of these values is taken to represent MIP or MEP. After the respiratory warm-up, MFVLs were performed to ascertain a number of lung function measures including forced expired volume (FEV), $FEV_{1.0}$ (forced expiratory volume over the first second of expiration) and peak inspiratory/expiratory flow rates (PIF/PEF, respectively). The MFVLs were accepted if they met several acceptability and reliability criteria (Appendix F). From these results, it was possible to determine the expired volumes (from TLC) that were required to achieve the lung volumes identified for testing. Online lung volume feedback in achieving these volumes was provided by OxyCon software (OxyCon Pro, Jaeger, Hoechberg, Germany).

Once valid MFVLs had been achieved, MIPs at specified percentages of total lung capacity ($\%_{TLC}$) and MEPs from TLC were performed. All MIP and MEP measures were taken using a portable mouth pressure meter (MPM). Performing MIPs at selected lung volumes produced a pressure-volume relationship for each athlete. All of these measurements were randomised to remove any possible order effects; the order of these measures can be found in Table 1. The MFVLs are the exception to this randomising, as they were all performed together.

Table 1. Order of MIP and MEP testing measures

RV	50%	MEP@TLC	75%	25%	TLC
50%	MEP@TLC	75%	25%	TLC	RV
MEP@TLC	75%	25%	TLC	RV	50%
75%	25%	TLC	RV	50%	MEP@TLC
25%	TLC	RV	50%	MEP@TLC	75%

After these lung function measures had been performed, the athlete was allowed 2 minutes recovery time before continuing with the whole body warm-up and maximal *dynamic* rowing strokes (power strokes) on the ergometer (Model C, Concept II, Nottingham, UK). Once the whole body warm-up was completed (see Section 3.3.2), the flywheel was standardised by stopping the rotation of the flywheel and vanes. With the handle in the brace, the participant established one of the lung volumes to be tested in the finish position. These volumes were randomised to minimise any learning effects, and performed in the following order (left to right, top to bottom):

Table 2. Order of lung volumes attained for rowing strokes

RV	50%	TLC	25%	S-S	75%
50%	TLC	25%	S-S	75%	RV
TLC	25%	S-S	75%	RV	50%

Immediately after establishing the lung volume, the athlete proceeded with the recovery phase of the stroke, picked up the ergometer handle and performed a single, maximal stroke on the ergometer, replacing the handle back in the brace each time. One minute was allowed between each stroke, which allowed enough time between each effort for the athletes to recover, prepare themselves, and to re-establish a dead flywheel. After all of the dynamic strokes had been performed, a recovery period of 20 minutes was allowed, and the whole procedure was repeated for the static (force) manoeuvres. The static manoeuvres required the ergometer chain to be tethered and secured in order to enable the measurement of handle force. In addition, MIP, MEP and MFVL measurements were also taken post testing to check for RMF.

The second of the two visit to the laboratory took a very similar line to the first; however, there was the addition of the RMF protocol, which was undertaken prior to any ergometry. Due to the nature of recovery after a maximal fatiguing effort, the time taken to record measurements post-RMF was crucial, as we wished to assess power and force production in a fatigued state. The 'window of opportunity' for testing in a fatigued state is unclear, although as stated earlier, complete recovery of the inspiratory muscles after fatigue takes at least 30 minutes. As there were six lung volumes to be tested and each lung volume takes finite time to be tested, it was crucial to test all lung volumes quickly. After the RMF protocol, MFVLs, MIP and MEP measurements were recorded and repeated three times. This was completed in order to establish the presence, or otherwise, of inspiratory and expiratory muscle fatigue. In order to facilitate a speedy testing session, the recovery period between strokes was reduced to 30 seconds. There was a brief 5-minute rest period between the testing blocks, as this was needed to alter ergometer setup. The total time taken to perform both testing blocks including the setup change to the ergometer, did not exceed 23 minutes. It should be noted here that the two visits to the laboratory were random so as not to induce any learning effects, so some athletes performed the fatigued session first, whilst others performed the un-fatigued measures first.

3.3 Procedures

3.3.1 The Testing Schedule

All of the athletes visited the laboratory on two occasions. The second visit involved the fatiguing protocol, and the recording of the fatigued lung volume measurements. A whole body warm-up was completed immediately before the fatiguing respiratory muscle protocol. Details of this protocol can be found below in Section 3.3.3. Timelines for the two sessions can be found below in Figure 7, with more extensive descriptions below in Section 3.3.4.

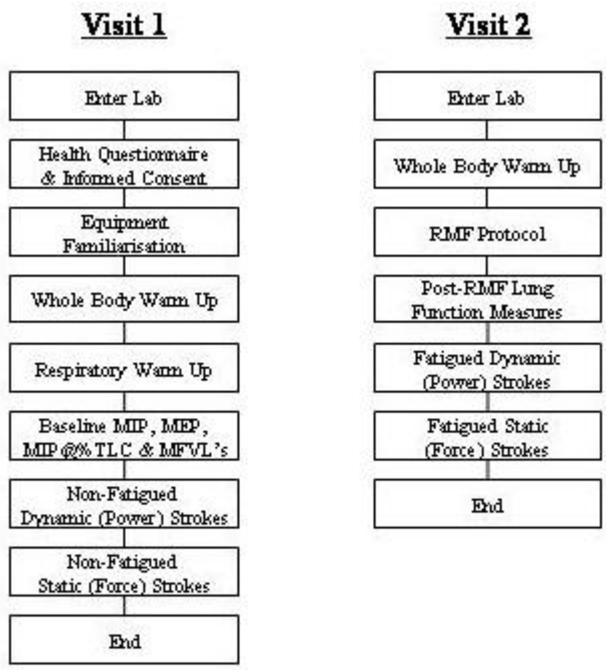

Figure 7. Timelines for each participant's visit to the laboratory

3.3.2 Pre-Testing Warm-Ups

Two warm-ups were used in this investigation. Firstly, before all of the ergometer work for both trials, a whole body warm-up (WBWU) on the rowing ergometer was completed. The intensity of this warm-up was related to the individual's personal best for a 2,000 m maximal effort piece (Appendix D). This was to ensure that the athlete was prepared for the subsequent maximal efforts. The second warm-up was a specific respiratory warm-up (RWU) based upon a study performed by Volianitis, et al., 1999, which consisted of 2 sets of 30 breaths against a pressure threshold load, equivalent to 40% of the individual's maximal inspiratory pressure, with a 1-minute rest between sets. Frequency of breathing (f_B) and duty cycle (d.c; T_I/T_{TOT}) were not specified, however, each participant was required to achieve RV after expiration before maximal inspiration to TLC, thus utilising the whole 'range' of the inspiratory muscles shortening. The RWU protocol has its benefits, as it is effective in enhancing the functional capacity of the inspiratory muscles, whilst decreasing inspiratory muscle fatigue and associated dyspnoea (Volianitis, et al., 2001b), and when combined with the WBWU protocol, proved to be a superior warm-up routine for all-out efforts on the ergometer (Volianitis, et al., 2001b). The RWU and WBWU were completed at each of the two visits to the lab, before any lung function measures were taken to ensure the athlete was in an optimum state to perform the tests.

3.3.3 The Fatiguing Protocol

The force and power production were assessed in both the 'fresh' state and after a fatiguing bout of inspiratory muscle work. This consisted of breathing against a respiratory load determined by the maximal inspiratory pressure of the individual. Given this maximal inspiratory pressure and a breathing frequency, a breathing protocol can be designed to produce parameters known to induce fatigue of the respiratory muscles.

The ability of the respiratory muscles to sustain an increased inspiratory load depends upon two ratios – the respiratory duty cycle and percentage maximal inspiratory pressure per breath. The product of these ratios is termed the Tension-Time Index (TTI; Roussos, et al., 1979; Zocchi, et al, 1993).

$$TTI = \frac{P_{insp}}{MIP} \times \frac{T_I}{T_{TOT}}$$

Where T_I = Inspiratory Time, T_{TOT} = Total time for one breath, P_{Insp} = Inspiratory pressure per breath (MIP being Maximal Inspiratory Pressure)

When constructing a fatiguing protocol for the inspiratory muscles, the TTI has to exceed 0.15 in order to fatigue the diaphragm (Rochester, 1985; Bellemare & Grassino, 1983), and 0.3 in order to fatigue the rib cage muscles (Zocchi, et al., 1993) and induce task failure. The protocol employed in the present study involved having the subject inspiring against a pressure threshold load equivalent to 80% baseline MIP pressure, at a breathing frequency (f_B) of 15 breaths per minute, and a duty cycle of 0.6. Expiration was unloaded. This protocol is known to fatigue the respiratory muscles within 10 minutes and had proven to do so in pilot testing. Additionally, the TTI for this protocol was calculated at 0.48, which is in excess of that required to induce both diaphragm and rib cage muscle fatigue.

The fatiguing protocol used a modified POWERbreathe (POWERbreathe™, Gaiam Ltd. Southam, Warwickshire, UK). The POWERbreathe was modified by drilling a small hole near the mouthpiece in order to connect a tube to an electromanometer (Mercury Electronics, Glasgow, UK), and replacing the expiratory valve with a large, standard one-way breathing valve to allow rapid, resistance-free expiration. The electromanometer was connected to an AC-DC transformer (Mercury Electronics, Glasgow, UK), and finally through an analogue to digital converter (DAQ Card AI-16XE-50, National Instruments Corporation [U.K] Ltd, Newbury, UK). The converter was connected to a laptop, and used with bespoke software written for the procedure (IMF Test Protocol using LabView software) to provide real-time feedback. The software displayed a manually-generated template for the athlete to follow, which was achieved by inputting the relevant MIP pressure, breathing frequency and duty cycle for the protocol desired. The software also offered real-time feedback of inspiratory and expiratory pressures generated by the athlete. The subject breathed against the load until voluntary failure, after which the presence of fatigue was confirmed by measuring maximal inspiratory mouth pressure.

The recovery time from this form of fatiguing protocol is unknown, and it is likely that the inspiratory muscles would start to recover during the subsequent power and force testing procedures. However, it is likely that the effort required of the inspiratory muscles during the stroke efforts would prolong recovery. In light of this, complete respiratory muscle fatigue could not be assumed for the full duration of the testing, however, this was accounted for through half of the participants performing the power strokes first and force strokes second.

Recreating the fatigue that is induced from a rowing race or intensive training piece proved to provide some problems. Ideally, a maximal 2,000 m ergometer test was to be used, however, it was decided that the test should isolate the fatiguing protocol to the respiratory muscles using a respiratory muscle fatiguing (RMF) protocol. The inspiratory muscles hold such significant influence in the context of postural stability and force/power transmission that it was thought reasonable to focus solely on these muscles. It was also important not to create a condition whereby it was impossible to distinguish the effects of fatigue between different muscle groups.

3.3.4 The Ergometer

Maximal single strokes can be very physical, as this is usually due to an emphasis on power production rather than technique. In light of this, weights were placed on and around the ergometer to minimise the amount of potential ergometer slippage that could occur during a maximal drive. The ergometer itself was used to record two sets of measurements; force and power.

Originally, a bespoke ergometer that provided both force and power across the entire stroke was to be used, however, after pilot testing, it was found to be highly inaccurate, therefore the ergometer of choice became a standard Concept II ergometer (Model C, Concept II, Nottingham, UK), widely used by rowers for everyday training. Power was measured by using the standard software that is embedded within every Concept II ergometer, with the monitor of the ergometer selected to display Watts as the output of choice. Force is not an output that is available as standard with a Concept II ergometer, and as a result, the setup of the ergometer differed in order to be able to record force outputs of a single stroke. This required the addition of a force transducer. In the context of the thesis, power strokes will be referred to as *dynamic* strokes, and force strokes referred to as *static* strokes. The setup required for both static and dynamic strokes are described below.

3.3.4.1 Dynamic (Power) Setup

Essentially, the ergometer was left as standard for this section of the testing. The monitor on the ergometer was selected to display wattage as the output of choice, with the damping adjusted to a drag factor relative to the individuals' weight (135 for heavyweight, >72.5 kg; 130 for lightweight, <72.5 kg; Mayglothling, 2002). The drag on the ergometer was adjusted by turning on the monitor, then pressing the 'reset' and 'ready' buttons simultaneously and rowing for a few strokes. Drag factor was used instead of a drag 'number' (i.e. 1 to 10) as used in previous studies as this accounts for any environmental changes, any wear which may occur to the ergometer flywheel, or for any dirt blocking the cages, whereas a standard drag number does not.

After some discussion and some pilot testing, it was decided that a dead-flywheel was the most reliable starting point. Although the moment of inertia for the flywheel has to be overcome, it is incredibly difficult to standardise the flywheel to a given 'speed' (indicated by the Watts output on the ergometer) before every maximal stroke. Slight differences in 'speed' at attempted dynamic standardisation will result in a different rate of deceleration of the flywheel, and differences in time between 'standardisation' and stroke performance will affect the load at the pick-up, which is not reliable enough for this test. With a dead flywheel, every stroke can be from a standardised point. This creates a more reliable starting point, and essentially recreates the first stroke of a race. From the finish position, the athlete proceeded with the recovery phase, and then completed the single maximal effort.

3.3.4.2 Static (Force) Setup

The set up of the ergometer for the static trials was subtly different to the dynamic stroke, whereby the athlete did not perform a rowing stroke in the normal sense. The chain attached to the ergometer handle was tethered to the ergometer frame, therefore not allowing the athlete to complete the normal drive phase. Additionally, a calibrated load cell (Model ABA Ergo Meter, Globus Italia, Codogne, Italy) was placed in line with the ergometer chain and attached to the handle; the transducer giving an output via a display on the handheld unit. The force transducer was calibrated by using software written into the force transducer system. The calibration was performed by hanging known weights from the ergometer handle and inputting the respective force output into the handheld unit. The length of the chain from the tether to the ergometer handle varied with each athlete, the length of the chain being long enough to enable the athlete to perform the static stroke with their legs flexed as they would be for the catch position. This setting places the athlete’s legs in the position they would normally find themselves in at the beginning of the stroke, where the application of force is at its most critical.

3.3.4.3 Power/Force Reliability Assessment

The test-retest procedure for the power/force results consisted of one individual performing all manoeuvres for both force and power as noted in Table 2, Section 3.2.1, over two days. This individual was considered to be representative of the group used for the study, as the individual trained and competed at the same level of international competition, however, this individual was not one of the group that participated in the study. This individual was also used for the pilot study of internal pressures; again using the protocol set out in Table 2, Section 3.2.1, but only for the power data as static strokes were not performed.

3.3.5 Balloon Catheter Setup for Pilot Study

The ergometer was left as standard for the duration of the pilot pressure study, the only real additions of equipment was that of the oesophageal balloon setup that was required to measure the pressures being created during the piece.

The catheters and balloons were placed in the stomach and oesophagus of a single subject in order to measure intra-abdominal, intra-thoracic, and consequently trans-diaphragmatic pressure. These pressures were recorded using two conventional balloon-tipped catheters (Oesophageal Balloon Catheter Set, Cooper Surgical, Berlin, Germany), which were passed per nasally, and then gradually swallowed into the oesophagus via the subject's normal peristalsis as a result of swallowing small amounts of water through a straw. Prior to the passing of the balloons, a lidocaine gel was applied in the nasal cavity and nasopharynx to minimize any discomfort of the balloons being placed.

Continuous measurement of pressure facilitated placement of the balloons. Placement in the lower third of the oesophagus was ensured by a negative pressure of 2 to 5 cmH_2O at (relaxed) end-expiration of functional residual capacity (FRC). Placement of the balloon no more than 6 to 8 cm into the stomach was ensured as the insertion of the catheter was terminated when the pressure on inspiration moved in a positive direction.

Once in place, about two *ml* of air was placed into each balloon. This inflated the balloon to about 3 to 4 mm in diameter. Each catheter was connected to a differential pressure transducer (Model DP45, Validyne, Northridge, California, USA), and each transducer was calibrated across the physiological range with an electromanometer (Model M14, Mercury, Glasgow, Scotland). The pressure signals were then passed through an amplifier (Model 1902, Cambridge Electronic Design, Cambridge, UK), digitized at sampling rates of 150 Hz and 3 kHz respectively, using an analogue-to-digital converter (Micro 1401 mkII, Cambridge Electronic Design, Cambridge, UK), and acquired on a personal computer running commercially available software (Spike 2 Version 5.12, Cambridge Electronic Design, Cambridge, UK).

Once the testing had been completed, very little effort was required for withdrawal of the balloon catheter, which was performed by a smooth, swift extraction, taking care not to cause discomfort to the participant. To ensure good placement and removal of the oesophageal balloons, a member of staff experienced in balloon placement was present to complete the manoeuvres. Contact was made with all participants a day after each testing occasion to ensure that delayed complications had not occurred. A more detailed method of balloon technique and evaluation procedures can be found by the authors Mead, et al. (1955) and Baydur, et al. (1982) (both articles cited in Taylor, How & Romer, 2006).

3.4 Statistical Analyses

In order to confirm that all results obtained from the measuring equipment were reliable, it was necessary to perform some test-retest measures. Many papers have already assessed the use of Mouth Pressure Meters (MPMs) to derive inspiratory and expiratory pressures, and this measurement is generally accepted to be accurate and reliable (Romer & McConnell, 2004). The Bland and Altman method of statistical agreement (Bland & Altman, 1986) was used to determine the reliability of various measures in the current study. The Bland & Altman plot is a statistical method usually used to compare two measuring techniques, although in this study it has been used to assess the reliability of measuring apparatus. It produces a graphic, which shows the differences between two measures plotted against the average of the two measures. There are also 3 horizontal lines plotted to represent the mean difference, and the mean difference ±1.96 times the standard deviation of the difference. The Bland & Altman plot is useful to reveal a relationship between the differences and the averages, to look for any systematic bias, and to identify possible outliers. If there is a consistent bias, it can be adjusted for by subtracting the mean difference from the new method. If the differences within the mean ± 1.96 SD are not functionally important, the measure can be deemed reliable. In the present study, the Bland and Altman method was used to assess the MIP and MEP measures, as well as the reliability of power/force results at all lung volumes.

One way repeated measures ANOVAs were performed on the data, in order to test for an effect of both lung volume and fatigue on force and power outputs. In cases where the ANOVA found no significance, but where the P value was close to 0.05, and the effect size was large, a parsimonious approach was adopted, and paired t-tests with Bonferroni adjustment were conducted to assess any potential statistical significance.

Chapter 4: Results

4.1 Participant Data

A number of lung function measures were assessed using MFVLs, as well as MIP and MEP measures. The results are reported below Table 3.

Table 3. Descriptive statistics for lung function measures (n = 9)

Lung Measure	Mean	Standard Deviation
Vital Capacity (VC, *l*)	7.15	1.150
Forced Expired Volume over first second ($FEV_{1.0}$, *l*)	5.32	0.709
Percentage $FEV_{1.0}$ ($FEV_{1.0}$/VC)	76.5	8.259
Peak Inspiratory Flow (PIF, $l.s^{-1}$)	8.41	1.848
Peak Expiratory Flow (PEF, $l.s^{-1}$)	11.1	1.192

4.2 Test-Retest Data

Individual plots for ergometer power, handle force, MIP and MEP can be found in Appendix H, however, the tables containing relevant statistics associated with these figures can be found below at Tables 4a-c. Results from the Bland & Altman tests showed good agreement between the power figures at the different lung volumes and also between MIP and MEP measures ($p>0.05$).

Table 4a. Ratio limits of agreements (LoA) for power at prescribed lung volumes

Variable	Bias			Random Error			n = 9
	Ratio	SE	95%CI	Ratio	SE	95%CI for lower LoA	95%CI for upper LoA
RV	0.997	0.013	-0.030 to 0.024	1.124	0.021	0.845 to 0.930	1.078 to 1.163
25%	1.006	0.009	-0.012 to 0.024	1.082	0.014	0.901 to 0.959	1.060 to 1.117
50%	0.988	0.007	-0.027 to 0.003	1.066	0.011	0.904 to 0.951	1.030 to 1.076
75%	1.012	0.007	-0.002 to 0.026	1.063	0.011	0.930 to 0.974	1.053 to 1.098
TLC	1.008	0.009	-0.010 to 0.027	1.084	0.014	0.901 to 0.960	1.063 to 1.122
S-S	1.006	0.006	-0.007 to 0.019	1.058	0.010	0.931 to 0.972	1.044 to 1.085

Table 4b. Ratio limits of agreements (LoA) for force at prescribed lung volumes

Variable	Bias			Random Error			**n = 9**
	Ratio	SE	95%CI	Ratio	SE	95%CI for lower LoA	95%CI for upper LoA
RV	0.996	0.014	-0.032 to 0.024	1.131	0.022	0.836 to 0.926	1.081 to 1.171
25%	1.019	0.010	-0.001 to 0.040	1.093	0.016	0.901 to 0.965	1.082 to 1.146
50%	0.988	0.011	-0.034 to 0.010	1.099	0.017	0.864 to 0.933	1.052 to 1.121
75%	0.944	0.012	-0.030 to 0.018	1.108	0.018	0.860 to 0.935	1.064 to 1.138
TLC	0.983	0.008	-0.034 to 0.000	1.077	0.013	0.886 to 0.940	1.031 to 1.085
S-S	0.996	0.007	-0.017 to 0.010	1.061	0.011	0.917 to 0.961	1.036 to 1.079

Table 4c. Ratio limits of agreements (LoA) for MIP and MEP measures

Variable	Bias			Random Error			**n = 9**
	Ratio	SE	95%CI	Ratio	SE	95%CI for lower LoA	95%CI for upper LoA
MIP @ RV	1.002	0.009	-0.016 to 0.020	1.076	0.013	0.904 to 0.958	1.052 to 1.105
MEP @ TLC	1.007	0.006	-0.005 to 0.019	1.033	0.006	0.962 to 0.987	1.028 to 1.053

4.3 Respiratory Function Measures

A one-way repeated measures analysis of variance (ANOVA) was conducted upon all lung function measures, to compare the triplicate data at each lung volume. The mean and standard deviation of the athletes' best efforts (subject to acceptability and reproducibility criteria; see Appendix F) are presented in Section 4.1. There were no significant differences between individual participants' lung function measures ($p>0.05$; Wilks' Lambda).

4.4 Pressure-Volume Relationship

The descriptive data for the inspiratory pressures generated at the specified lung volumes are presented in Table 5a, and the averages in Table 5b. Three measurements were made at each volume for every participant during a single testing session. MEP measures from TLC were also taken, and can be found in Table 5c. A one-way repeated measures ANOVA was performed on the inspiratory pressure data to assess the agreement between the three measurements made. There were no significant differences between inspiratory or expiratory pressures within subjects at any of the lung volumes ($p>0.05$; Wilks' Lambda).

Table 5a. Descriptive statistics for inspiratory pressures for each trial at each lung volume

	Lung Volume	n	Mean (cmH_2O)	Standard Deviation
Trial 1	Residual Volume (RV)	9	144.3	46.6
	25%	9	123.4	31.7
	50%	9	98.1	24.2
	75%	9	63.7	14.3
	Total Lung Capacity (TLC)	9	7.0	6.8
Trial 2	Residual Volume (RV)	9	133.7	33.5
	25%	9	122.4	33.7
	50%	9	100.3	20.2
	75%	9	59.0	15.7
	Total Lung Capacity (TLC)	9	3.6	7.8
Trial 3	Residual Volume (RV)	8	133.9	27.9
	25%	9	121.0	34.6
	50%	9	93.7	19.8
	75%	9	52.2	9.2
	Total Lung Capacity (TLC)	9	4.7	5.3

Table 5b. Descriptive statistics for average inspiratory pressures over all three trials at each lung volume ($n = 9$)

Lung Volume	Mean (cmH_2O)	Standard Deviation
RV	137.5	34.6
25%	122.3	32.4
50%	97.4	20.1
75%	58.3	12.0
TLC	5.1	5.9

Table 5c. Descriptive statistics for average MEP @ TLC over all three trials (n = 9)

	Mean (cmH_2O)	Standard Deviation
MEP	153.2	40.9

A one-way repeated measures ANOVA was performed on the inspiratory results to assess differences between pressure production at the specified lung volumes. There were statistically significant differences (p = 0.001) between the inspiratory pressures generated at almost all of the lung volumes (Wilks' Lambda = 0.039, F [4, 5] = 30.683, multivariate eta squared = 0.961). Post-hoc comparisons using Bonferroni adjustment identified where these differences occurred; see Table 6. A mean plot of the pressure-volume relationship is shown in Figure 8.

Table 6. Results of repeated measures ANOVA performed on average inspiratory data (cmH_2O) between lung volumes. (Bold figures indicate significant differences between volumes).

	RV	25%	50%	75%	TLC
RV	X	0.386	**0.006**	**0.001**	**0.000**
25%		X	**0.016**	**0.001**	**0.000**
50%			X	**0.001**	**0.000**
75%				X	**0.000**
TLC					X

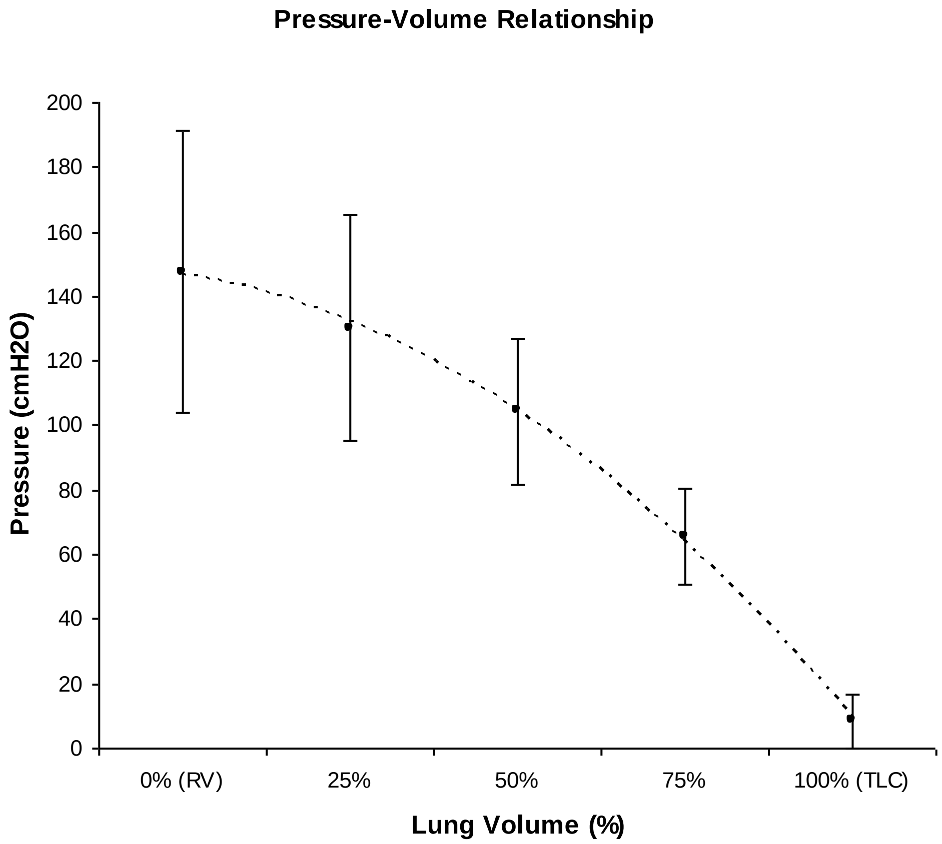

Figure 8. Relationship between maximal inspiratory pressures and lung volume

4.5 Efficacy of Inspiratory Muscle Fatigue Intervention

It was necessary to test the IMF intervention in order to confirm its ability to induce inspiratory muscle fatigue. In addition, MEP was assessed to ensure that the IMF intervention did not also induce expiratory muscle fatigue even though it was not expected. Descriptive data can be found in Tables 7 and 7a.

Table 7. Pre Vs. Post IMF MIP measures (cmH_2O)

Subject	Pre IMF	Post IMF (Av)	Change	% Change
1	107	62.33	-44.67	-41.74
2	149	89.33	-59.67	-40.04
3	201	126.3	-74.67	-37.15
4	205	140.7	-64.33	-31.38
5	135	96.33	-38.67	-28.64
6	161	116.00	-45.00	-27.95
7	201	153.00	-48.00	-23.88
8	152	95.67	-56.33	-37.06
9	128	81.67	-46.33	-36.20
Average	159.89	106.81	-53.07	-33.78

Table 7a. Pre Vs. Post IMF MEP measures (cmH_2O)

Subject	Pre IMF	Post IMF	Change	% Change
1	188.7	190.7	2.00	1.06
2	121.7	141.0	19.33	15.89
3	225.0	198.3	-26.67	-25.19
4	132.3	156.7	24.33	18.39
5	98.0	117.3	19.33	19.73
6	140.7	154.3	13.67	9.72
7	179.7	186.0	6.33	55.43
8	168.0	170.3	2.33	1.39
9	184.7	184.3	-0.33	-0.18
Average	159.9	166.6	6.70	6.41

Paired t-tests on the Pre vs. Post IMF data indicated that the IMF intervention induced a significant fall in MIP measures ($p = 0.000$, $t = 13.821$, $df = 8$), whilst not significantly affecting MEP measures ($p = 0.376$, $t = -0.938$, $df = 8$). The Eta squared statistics for MIP and MEP were 0.960 and 0.099, respectively.

4.6 Force-Volume Relationship

4.6.1 Force without Inspiratory Muscle Fatigue

A one-way repeated measures ANOVA was conducted upon the force data at each of the lung volumes in order to assess the agreement between the triplicate measures of force at each lung volume; all three measurements were made for each volume during a single testing session, but in a randomised order (see Table 3 in the Methods Section 3.5.3). The descriptive data for the force data at each lung volume is presented in Table 8a. There were no significant differences between force measurement within subjects at any of the lung volumes (p>0.05; Wilks' Lambda).

Table 8. Descriptive statistics for force production for each trial at each lung volume

	Lung Volume	n	Mean (N)	Standard Deviation (N)
Trial 1	RV	8	1296	253.1
	25%	9	1329	232.3
	50%	9	1286	241.0
	75%	9	1329	253.9
	TLC	9	1313	253.5
	S-S	9	1365	222.8
Trial 2	RV	8	1283	278.4
	25%	9	1302	245.6
	50%	9	1312	250.9
	75%	9	1293	265.4
	TLC	9	1310	246.3
	S-S	9	1324	259.0
Trial 3	RV	8	1266	288.0
	25%	9	1286	262.1
	50%	9	1335	287.0
	75%	9	1321	287.3
	TLC	9	1342	306.5
	S-S	9	1350	274.5

The average self-selected lung volume for the force trials was 35.64% [±17.03%] of TLC, which should equate to a force production of approximately 1310 N. However, the actual S-S force figure was 30 N higher (1346 N ± 244 N). A one-way repeated measures ANOVA was performed on the average of the force data for each lung volume. There were no statistically significant differences ($p = 0.142$) between the force produced at any of the lung volumes; Wilks' Lambda = 0.131, $F [5, 3] = 3.997$, multivariate Eta squared = 0.869. A mean plot of the force-volume relationship can be found in Figure 9.

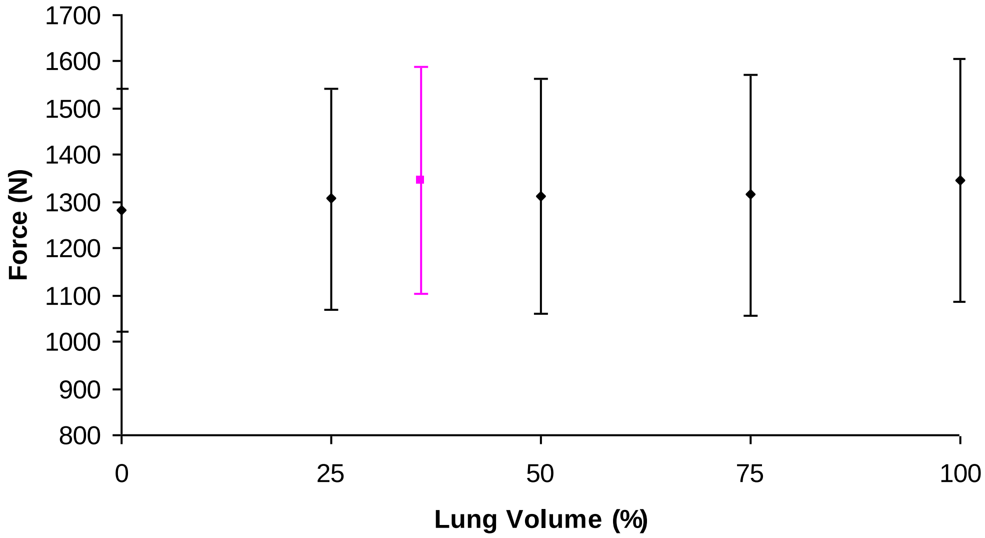

Figure 9. Relationship between un-fatigued force production and lung volume across all participants (♦ = prescribed lung volumes, ■ = s-s lung volume)

4.6.2 Force with Inspiratory Muscle Fatigue

A one-way repeated measures ANOVA was conducted upon the fatigued force data at each of the lung volumes in order to assess the agreement between the triplicate measures of force production at each lung volume. The descriptive data for the fatigued force data at each lung volume is presented in Table 9. There were no significant differences between force generated within subjects at any of the lung volumes ($p>0.05$; Wilks' Lambda.

Table 9. Descriptive statistics for fatigued force production for each trial at each lung volume

	Lung Volume	N	Mean (N)	Standard Deviation (N)
Trial 1	RV	9	1178	237.3
	25%	9	1251	219.0
	50%	9	1209	223.4
	75%	9	1207	224.2
	TLC	9	1183	220.6
	S-S	9	1238	210.5
Trial 2	RV	9	1151	265.0
	25%	9	1224	247.7
	50%	9	1220	223.0
	75%	9	1220	238.7
	TLC	9	1198	223.0
	S-S	9	1218	211.5
Trial 3	RV	9	1174	277.2
	25%	9	1227	256.3
	50%	9	1216	240.3
	75%	9	1221	244.3
	TLC	9	1218	232.7
	S-S	9	1221	247.5

The average S-S lung volume for the fatigued force trials equated to 28.5% [±10.12%] of TLC, which should equate to a force production of approximately 1235 N. The actual S-S force figure was 1225 N ± 215 N. A one-way repeated measures ANOVA was performed on the fatigued force data at each of the lung volumes to explore any statistical differences between the lung volumes. There were no statistically significant differences ($p = 0.152$) between force production at any of the lung volumes; Wilks' Lambda = 0.208, $F [5, 4] = 3.044$, multivariate Eta squared = 0.792. A mean plot of the fatigued force-volume relationship can be found in Figure 10.

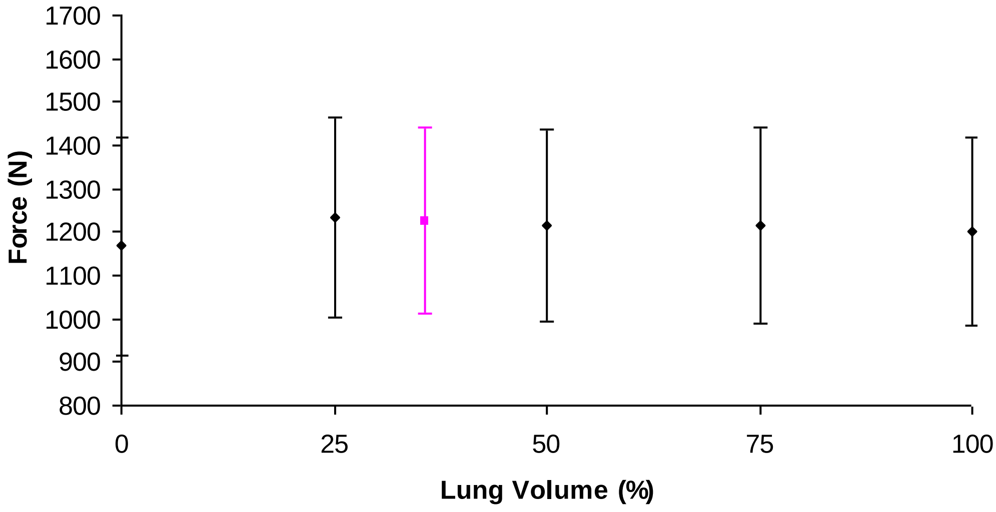

Figure 10. Relationship between fatigued force production and lung volume across all participants (♦ = prescribed lung volumes, ■ = s-s lung volume)

4.6.3 Comparison of Fatigued & Un-fatigued Force Data

A one-way repeated measures ANOVA was performed on the un-fatigued and fatigued data in order to assess the influence of the respiratory muscle fatigue on force production at each lung volume. The ANOVA revealed no significant difference between un-fatigued and fatigued force production ($p>0.05$; Wilks' Lambda) at any of the lung volumes. However, there were noticeable differences in force production across all lung volumes of 5.5 – 9.2%, and the results from the ANOVA were close to significance with a very large effect size ($p = 0.058$; Eta squared = 0.579). With this large effect size in mind, paired t-tests (with Bonferroni correction) were conducted. T-tests identified significant differences between the force production in un-fatigued and fatigued states at all volumes. The results of the t-tests are shown in Table 10, with a plot of this data shown at Figure 11.

Table 10. T-test results between mean un-fatigued and fatigued force data

Lung Volume	Un-fatigued Force (N)	Fatigued Force (N)	% Difference	p*	t	df
RV	1281	1168	-8.90	**0.001**	4.585	7
25%	1306	1234	-5.47	**0.001**	3.804	8
50%	1311	1215	-7.34	**0.000**	5.818	8
75%	1314	1216	-7.49	**0.001**	4.279	8
TLC	1322	1200	-9.24	**0.000**	5.171	8
SS	1346	1226	-8.97	**0.001**	4.119	8

* significance level has been adjusted for Bonferroni correction for repeated t-tests (∴ new significance level = 0.05 ÷ 6, $p < 0.008$; significant comparisons in bold)

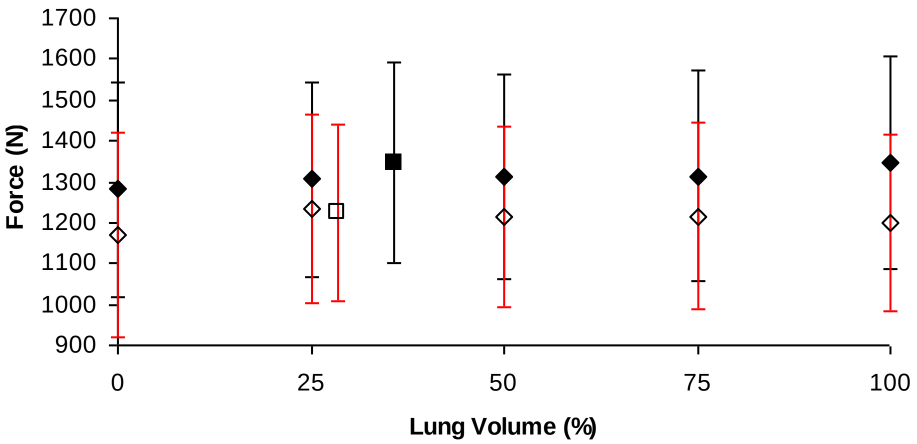

Figure 11. Relationship between un-fatigued force production, fatigued force production and lung volume across all participants. (♦ = un-fatigued results, ◊ = fatigued results, ■ = un-fatigued S-S, = fatigued S-S. Red error bars show standard deviation for fatigued results).

4.7 Power-Volume Relationship

4.7.1 Power without Inspiratory Muscle Fatigue

Three measurements were made for each volume during a single testing session, but in a randomised order. Two statistical analyses were conducted upon the power-volume data. A one-way repeated measures ANOVA was conducted upon the power data at each of the lung volumes in order to assess the agreement between the triplicate measurements of power production at each lung volume. The descriptive data for the power data at each lung volume is presented in Table 11. There were no significant differences between power figures within subjects at any of the lung volumes (p>0.05; Wilks' Lambda.

Table 11. Descriptive statistics for power production for each trial at each lung volume

	Lung Volume	N	Mean (W)	Standard Deviation (W)
Trial 1	RV	8	548.0	112.6
	25%	9	596.7	114.2
	50%	9	606.1	114.1
	75%	9	577.7	122.4
	TLC	9	606.7	102.1
	S-S	9	574.8	120.7
Trial 2	RV	8	569.9	131.3
	25%	9	610.2	122.7
	50%	9	599.0	139.5
	75%	9	599.3	140.6
	TLC	9	581.7	119.3
	S-S	9	574.1	121.1
Trial 3	RV	8	604.5	129.9
	25%	8	632.1	101.3
	50%	8	636.0	123.6
	75%	8	625.6	121.2
	TLC	8	638.9	111.1
	S-S	8	607.8	112.3

The average self-selected (S-S) lung volume for the power trials was 40.6% [±15.3%] of TLC, which should equate to a power production of approximately 615 W. However, the actual S-S power figure was 30 W lower (584 W ± 115 W). A one-way repeated measures ANOVA was performed on the average power data for each of the lung volumes. There were no statistically significant differences (p = 0.359) between power production at any of the lung volumes; Wilks' Lambda = 0.265, F [5, 3] = 1.662, multivariate eta squared = 0.735. A mean plot of the power-volume relationship can be found in Figure 12.

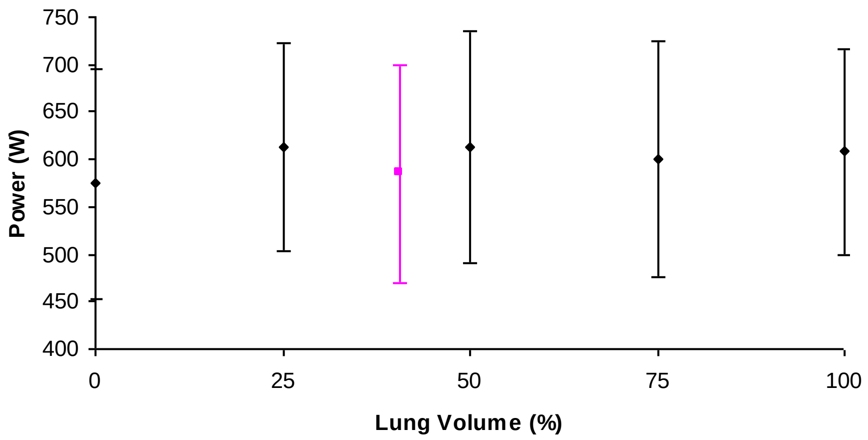

Figure 12. Relationship between un-fatigued power production and lung volume across all participants (♦ = prescribed lung volumes, ■ = s-s lung volume)

4.7.2 Power with Inspiratory Muscle Fatigue

A one-way repeated measures ANOVA was conducted upon the power data generated in the IMF state at each of the lung volumes in order to assess the agreement between the triplicate measures of power production in the fatigued state at each lung volume. The descriptive data for the fatigued power figures at the lung volumes are presented in Table 12. There were no significant differences between fatigued power data within subjects at any of the lung volumes ($p>0.05$; Wilks' Lambda).

Table 12. Descriptive statistics for fatigued power production for each trial at each lung volume (n = 9)

	Lung Volume	Mean (W)	Standard Deviation (W)
Trial 1	RV	554.3	129.3
	25%	597.9	115.7
	50%	592.8	114.4
	75%	605.7	105.8
	TLC	622.2	101.2
	S-S	600.8	95.3
Trial 2	RV	555.7	121.4
	25%	609.8	107.5
	50%	598.7	109.7
	75%	609.8	129.6
	TLC	606.1	94.4
	S-S	577.7	110.9
Trial 3	RV	544.9	125.6
	25%	611.3	107.3
	50%	592.2	102.5
	75%	594.7	113.0
	TLC	616.0	95.4
	S-S	578.1	93.8

The average self-selected (S-S) lung volume for the fatigued power trials was 28.03% [±12.83%] of TLC, which should equate to a power production of approximately 600 W. However, the actual S-S power figure was lower by 15 W (585 W ± 97 W). A one-way repeated measures ANOVA was performed on the averages of the fatigued power figures for each of the lung volumes (for the reasons mentioned previously) to explore the statistical differences between the lung volumes. There were no statistically significant differences ($p = 0.504$) between power production at any of the lung volumes (Wilks' Lambda = 0.438, $F [5, 4] = 1.025$, multivariate eta squared = 0.562). A mean plot of the power-volume relationship can be found at Figure 13.

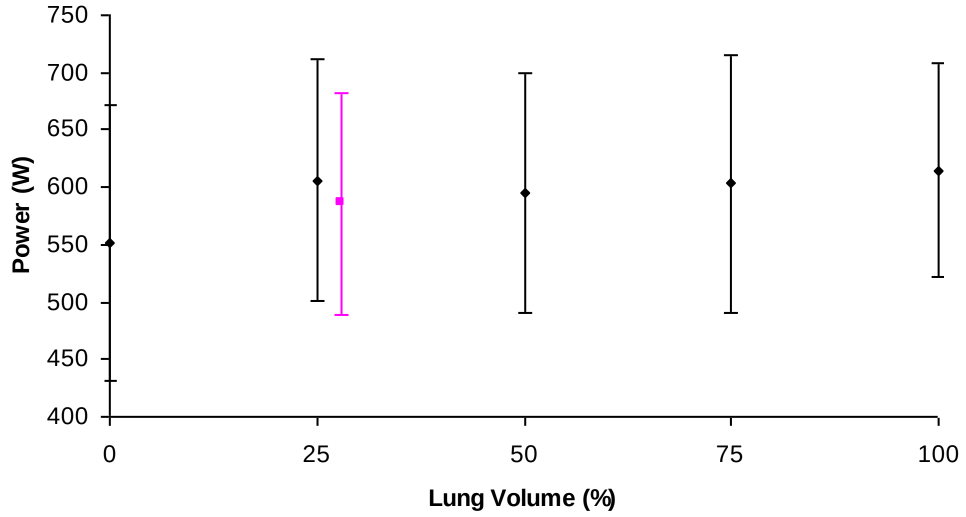

Figure 13. Relationship between fatigued power production and lung volume across all participants (♦ = prescribed lung volumes, ■ = s-s lung volume)

4.7.3 Comparison of Fatigued & Un-fatigued Power Data

A one-way repeated measures ANOVA was performed on the un-fatigued and fatigued data in order to assess the influence of the inspiratory muscle fatigue intervention on power production in a fatigued state. The ANOVA showed no significant difference between un-fatigued and fatigued power production ($p>0.05$; Wilks' Lambda) at any of the lung volumes. Results comparing un-fatigued and fatigued power production for all lung volumes can be found in Table 13, with un-fatigued vs. fatigued power results being shown in Figure 14.

Table 13. Results between mean un-fatigued and fatigued power data

Lung Volume	Un-fatigued Power (W)	Fatigued Power (W)	% Difference
RV	574.1	551.6	-3.92
25%	612.3	606.3	-0.97
50%	612.9	594.6	-2.98
75%	599.9	603.4	0.58
TLC	607.9	614.8	1.13
SS	584.7	585.5	0.14

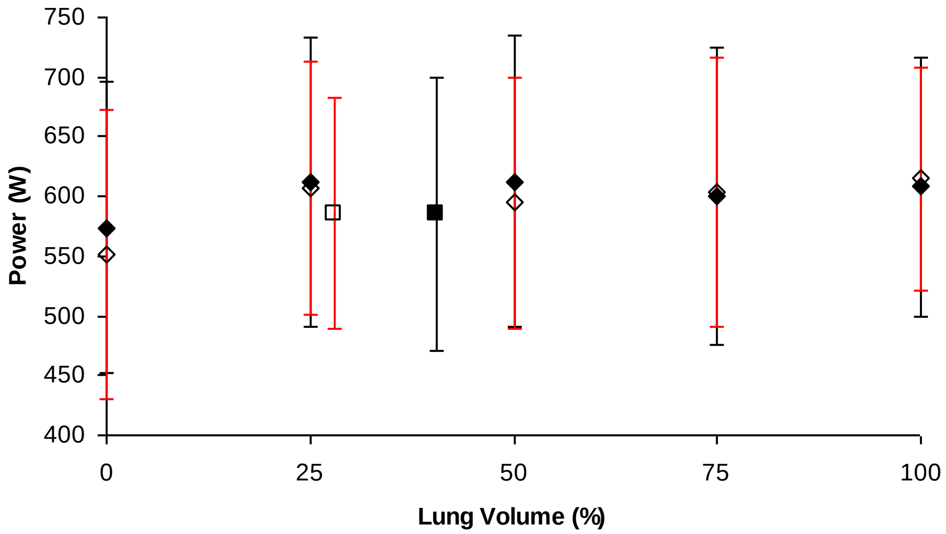

Figure 14. Relationship between un-fatigued power production, fatigued power production, and lung volume across all participants. (♦ = un-fatigued results, ◊ = fatigued results, ■ = un-fatigued S-S, = fatigued S-S. Red error bars show standard deviation for fatigued results).

4.8 The Self-Selected Lung Volume

4.8.1 The Influence of IMF

Paired sample t-tests were also performed on the percentage of TLC that was selected by the subjects as the S-S lung volume. The paired sample t-tests indicated that there was no significant difference between the S-S lung volumes achieved for the force and power trials, suggesting that the S-S volume selected by the participant for both force and power trials were similar. Eta squared statistics (0.362) indicated a large effect size. A summary of these results can be found in Table 14.

Table 14. T-test results between mean un-fatigued and fatigued self-selected lung volume data for power and force trials

	Pre-IMF S-S Volume (%TLC)	Post-IMF S-S Volume (%TLC)	% Difference	p*	t	df
Power (W)	40.55	28.03	12.52	0.066	1.423	7
Force (N)	35.64	28.46	7.18	0.152	0.790	7
Difference	4.91	0.43	4.48	0.051	1.583	8

*significance values have been adjusted with Bonferroni correction for repeated t-tests ($\therefore$ new significance level = 0.05 ÷ 3, $p < 0.017$)

4.8.2 Predicted Vs. Actual Force & Power

A paired samples t-test was performed on the Predicted vs. Actual Force and Power data generated during the testing. The S-S lung volume during the trials provided the actual data (as obtained during the testing), whilst the same volume percentage was applied to the trend produced over all the lung volumes, and an equivalent force/power measurement read off (predicted value). The results indicated that there were no significant differences between the predicted values the actual values ($p>0.05$), suggesting that it was possible to predict force and power output from the inspired volume.

4.9 Assessment of Study Power & Effect Sizes

To the best of the authors' knowledge, this is the first study to assess the effects of lung volume upon force and power production in the context of the rowing stroke, as well as the effects inspiratory muscle fatigue has upon these parameters. It was not possible to estimate the participant numbers that would be required to provide statistical power to the study and give meaning to the data derived from it. However, the data collected provided the opportunity to assess statistical power retrospectively. Accordingly, the effect size was calculated for nine subjects using the most reliable test-retest force and power data.

The most reliable test-retest data was taken, for both force and power, and used as the basis for the testing. The effect size measurement was manipulated in order to indicate the desirable sample size for the study. This gave us the smallest value for the effect size needed in our study to detect statistical significance. For force (which used the RV values as the basis for the comparisons), a 7.1% effect size was needed with an n = 9, and for power (which used the 25% values as the basis for comparisons), a 12.3% effect size was needed.

4.9.1 Lung Volume Effect Size

The number of participants needed to observe a significant effect of lung volume, of the magnitude that we measured, was also calculated using the Bland & Altman tables used to calculate LoA for Tables 4a-c, but adjusting the participant numbers in order to achieve a significant result. Results can be found below in Table 15. It should be noted that the effect size relates to the largest difference in lung volume that was observed.

Table 15. Effect sizes and associated participant numbers required for both force and power trials in fatigued and un-fatigued states to detect the influence of lung volume

	Force		Power	
	Effect Size Measured (%)	Numbers Needed	Effect Size Measured (%)	Numbers Needed
Un-fatigued	4.8	20	6.3	36
Fatigued	5.4	16	10.3	13

4.9.2 Fatigued Effect Size

With respect to the effects of fatigue, the results for the effect sizes found in this study and number of participants needed to identify these effect sizes can be found below in Table 16.

Table 16. Effect sizes and associated participant numbers required for both force and power trials to detect the influence of fatigue

	Force		Power	
	Effect Size measured (%)	Numbers Needed	Effect Size measured (%)	Numbers Needed
Largest Difference	9.24	**6**	3.92	94
Average Difference	7.9	**8**	1.62	544

(Bold figures indicate study had enough power to show effect)

4.10 Intra-thoracic, Intra-abdominal & Trans-diaphragmatic Pressures

A single subject pilot study was run alongside the main study, using the same protocol and testing procedures as the main study, but two balloon catheters were placed into the participant to measure gastric (P_{ga}; IAP), oesophageal (P_{oes}; ITP) and consequently trans-diaphragmatic (P_{di}) pressures. This was performed for both the power and force protocols, but only under un-fatigued conditions. The descriptive results of the pilot testing can be seen in Table 17, with plots of the pressure-volume relationships during the power and force trials being shown in Figures 15 and 16. Each point represents the maximum pressure produced for that lung volume over one effort, repeated three times, and averaged. Average stroke duration was not measured, but can be approximated to between 1 and 1.5 seconds (drive and recovery phases), based on stroke duration for the 30 s maximal effort piece.

Table 17. Descriptive statistics for the force and power-volume pressure trials (n = 1; figure represents highest absolute maximum during stroke phase).

	Power				**Force**			
	Power (W)	IAP (cmH_2O)	ITP (cmH_2O)	Pdi (cmH_2O)	Force (N)	IAP (cmH_2O)	ITP (cmH_2O)	Pdi (cmH_2O)
RV	255.3	101.68	127.23	19.76	1310.9	88.07	102.60	30.51
25%	258.6	146.57	80.01	73.61	1356.1	135.67	142.52	68.41
50%	308.6	165.13	90.56	83.04	1374.4	164.97	135.53	62.54
75%	269	154.19	107.18	67.58	1381.6	175.68	125.31	62.70
TLC	239.3	123.18	105.70	49.15	1407.7	152.01	148.13	40.78

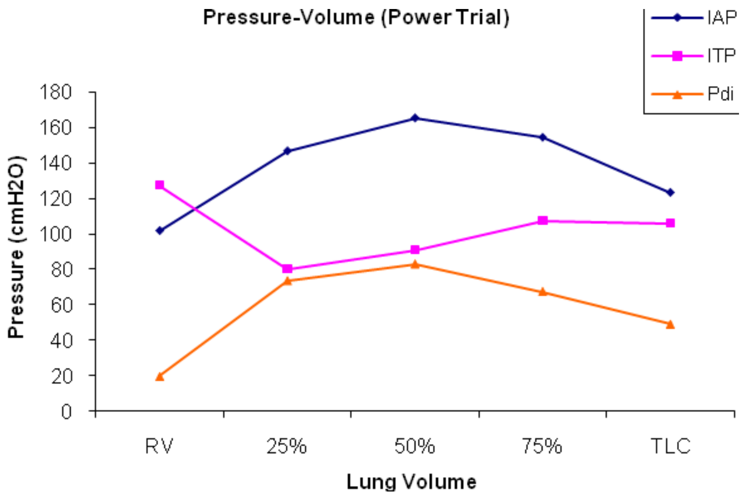

Figure 15. Pressure-Volume interaction during the power trial

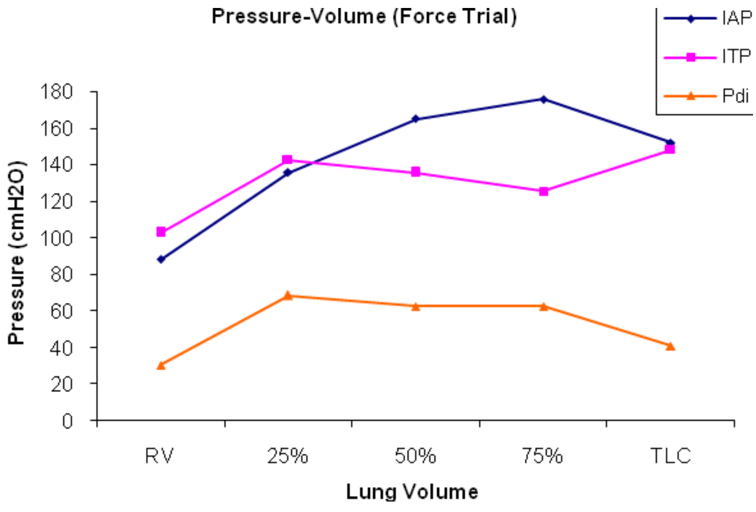

Figure 16. Pressure-Volume interaction during the force trial

As well as performing the protocol employed for the main study, an additional 30 s maximal effort piece was performed on the ergometer whilst the balloons were in place. A section of the piece can be seen in Figure 17, with an expanded section noting drive and recovery points being found at Figure 17a

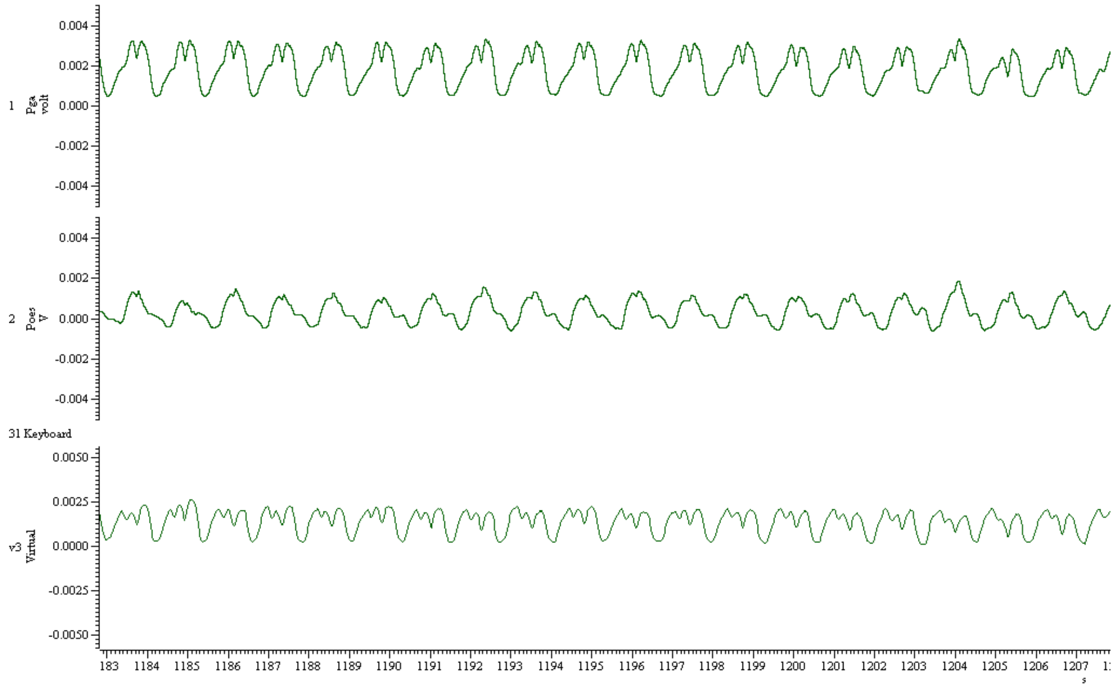

Figure 17. A section of the pressure traces resulting from the maximal effort piece with IAP (top), ITP (middle) and P_{di} (bottom) shown

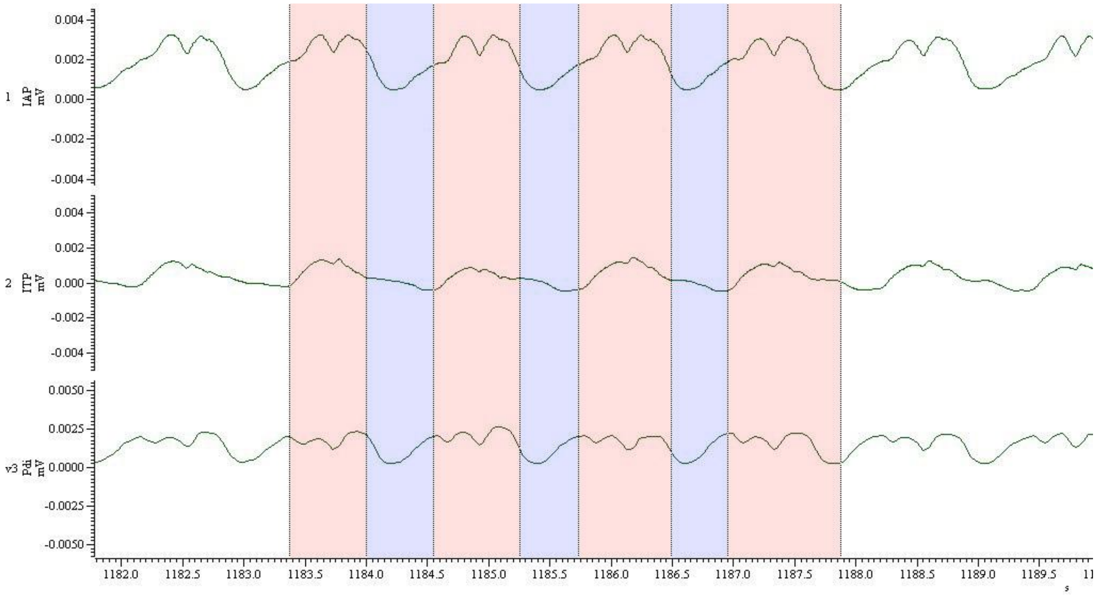

Figure 17a. Exploded section of the maximal effort piece showing drive (red) and recovery (blue) phases. LRC ratio is 1:1, with phases estimated from pressure swings - not directly assessed.

Pressure fluctuations were monitored constantly throughout the piece, with post-test analysis of the traces providing absolute figures for pressures. As the traces were measured in millivolts (mV), a conversion factor was applied to the figures to obtain values for pressure (cmH_2O). The calibration of the pressure transducer system and the conversion factor can be found in Appendix G. Absolute figures for the maximal effort piece can be found in Table 18.

Table 18. Absolute figures representing maximal point on each pressure traces during the maximal effort piece

Pressure	Max (cmH_2O)	Min (cmH_2O)	Average (cmH_2O)
IAP	144.7	7.46	73.59
ITP	75.00	-22.65	15.34
Pdi	111.8	7.09	58.83

Chapter 5: Discussion

5.1 Summary of Data

There was no significant effect of lung volume on either force or power production. However, prior inspiratory muscle fatigue induced a reduction in force production at all lung volumes. There was no detectable effect of prior fatigue upon power production. The effect of fatigue on the force trials resulted in greater differences between the un-fatigued and fatigued results with increasing lung volume, suggesting that the development of inspiratory muscle fatigue, may gradually limit the force production at the catch.

With reference to the hypotheses, the influence of specific inspiratory muscle fatigue did have an influence on force output. A potential mechanism for the decrement of force could be that the fatigued inspiratory muscles were unable to contribute as effectively to torso stability at the catch to allow for maximal force transference to occur. The potential for external abdominal compression at the catch from the lower limbs, their influence on the position and mechanical efficiency of the diaphragm, and the position of the measurement of force may also have an effect upon this relationship. The force produced (and the resultant mechanical torque on the boat's hull) is important with respect to performance, as it is required to either initially move the boat through the water, or to allow the boat to continue to travel through the water. A decrease in force output could potentially result in a decrease in performance.

5.2 Analysis of Fatiguing Protocol

The aim of this study was to identify the potential relationship between lung volume and force/power, as well as the influence of inspiratory muscle fatigue upon this relationship. The efficacy of the inspiratory fatiguing protocol was confirmed.

The TTI calculated for this study, 0.48, was known to induce inspiratory muscle fatigue within 10 minutes in non-athletes, however, the average fatiguing time for this protocol was in excess of 17 minutes, giving evidence that the significant amount of training employed by rowers enables them to resist inspiratory muscle fatigue during heavy respiratory demands. This information supports a number of findings showing that athletic individuals tend to possess stronger inspiratory muscles (Coast, et al, 1990; Martin & Stager, 1981). The longer time required to induce respiratory muscle fatigue also supports evidence that aerobic training does have an influence on respiratory muscle strength and fatigue resistance (McConnell, et al. 1996; Martin & Chen, 1982), since these rowers did not specifically train their respiratory muscles, yet they had higher inspiratory muscle pressures than untrained individuals, and a greater resistance to fatigue. The fact that rowing training appears to impart a training stimulus to the inspiratory muscles is perhaps unsurprising, given the evidence that the muscles of the torso contribute to force production during rowing. Indeed, the finding that IMF reduced force production provides further support for this notion. There is also direct evidence that respiratory muscle strength increases in response to non-respiratory training. DePalo, et al. (2004), noted that repeated, forceful, non-respiratory limb weight training manoeuvres strengthened the inspiratory muscles and increased diaphragm thickness. This work followed on from preliminary evidence by Al-Bilbeisi & McCool (2000) who noted that a number of weight lifting activities recruited the diaphragm, and increased P_{di} to a level that could provide a significant strength-training stimulus to the diaphragm. Pressure data collected during the current pilot study also indicate that full pressure rowing is associated with considerable pressure changes intra-thoracically and intra-abdominally, which also suggest that a non-specific training stimulus is applied to the respiratory muscles by rowing training.

Notwithstanding these observations, a significant amount of inspiratory muscle fatigue has been documented following a maximal effort rowing piece (Volianitis 2001a, Griffiths & McConnell, 2007). A typical maximal effort 2,000 m effort either on water, or an ergometer, lasts anywhere between 340 and 390 seconds for males dependent upon weight and ability. The isolated respiratory muscle fatiguing protocol employed by this study took, on average, greater than 1020 seconds, nearly 3 times as long to induce fatigue, albeit to a larger extent than that observed following rowing. It is known that the diaphragm fatigues more rapidly during exercise, and this has been ascribed to the competition between muscle vascular beds for blood. In addition, in the context of rowing, it is reasonable to suppose that the contribution of inspiratory muscles to stabilising the trunk in order to assist in the efficient generation and transmission of force production may contribute to the development of fatigue. If this is the case, higher force and power productions by an individual may exacerbate fatiguing of the respiratory muscles and contribute to loss of performance during ‘racing’ conditions.

5.3 Analysis of Force

There is no obvious relationship between the un-fatigued force trial and lung volume; there were no significant differences between force production at any of the lung volumes assessed. The lack of statistical significance for the un-fatigued trial is almost certainly due to the relatively small difference between the forces produced at the lung volumes (maximum difference = 122N), accompanied by the small numbers of participants involved in this study. The retrospective analysis showed that, although the difference in force production between the lung volumes in the un-fatigued trial were relatively small (4.8%), the number of participants needed to identify a change of 4.8% was more than double that used for this study (20 vs. 9). It is possible that by increasing participant numbers to those indicated by the post-hoc Limits of Agreement (LoA) testing may make this small effect of lung size significant, however, the only 'real' difference in the data is between RV and the other lung volumes, as, aside from RV, all other volumes produced similar results.

A similar pattern was observed for the fatigued data; the only 'real' difference occurring between RV and the rest of the data (Figure 11). Excluding the RV lung volume result, the fatigued force production tended to decrease with increasing lung volume, however there was no statistical significance between any of the lung volumes. Unfortunately, participant numbers for this study did not provide sufficient power to detect the effect of lung volume in either the fatigued or un-fatigued trials. Increasing the numbers for similar studies in the future to those identified would provide enough statistical power to determine whether these small differences for both un-fatigued and fatigued trials were physiological, or due to measurement error.

The comparison between the un-fatigued and fatigued force generated some interesting observations. Firstly, and perhaps most importantly, the participant numbers used for this study were theoretically sufficient to generate the statistical power required to detect changes brought about by the influence of fatigue. Secondly, the force produced at all lung volumes was lower in the fatigued state. Thirdly, the differences between the un-fatigued and fatigued force data (with the exception of the RV result) tended to become greater with increasing lung volume (Figure 11 & Table 10). This is relevant to the hypotheses for this study. It was hypothesised that the diaphragm acts as a stabilising mechanism for the body, and that it aids the transmission of forces though the body and out onto the oar or ergometer handle. It was also hypothesised that inspiratory muscle fatigue would have a negative effect on this function, and this proved to be the case. The tendency for this effect to be larger at higher lung volumes supports the results of the study by Yan, et al. (1992), who found that fatigue affects diaphragm contractility more at higher lung volumes than at low lung volumes.

5.4 Analysis of Power

The relationship between the un-fatigued power and lung volume proved to be quite variable, with no clear relationship between power and lung volume. As with the force data, there was no statistically significant difference between the powers produced at any of the lung volumes. Again, the small participant numbers for this study, and the relatively small effect size make it difficult to determine whether the lack of an effect is due to type 2 error. The lung volume effect size (6.3%) for the un-fatigued data was slightly larger than that for the force data (4.8%), but our population size did not yield the power to detect this difference statistically. Post-hoc testing on the power data indicated that a sample size some four times that used for the study would have been needed to generate sufficient statistical power to detect a 6.3% effect (Table 13). The effect of lung volume on the fatigued trial was greater than that for the un-fatigued trial (10.3%), and the sample size was only just lower than that to detect a 10.3% effect (9 vs. 13, respectively).

In contrast to the force results, there appeared to be no effect of inspiratory muscle fatigue upon power production. The largest difference occurred at RV (-3.92%), and the average difference was just -1.62%. The RV lung volume seemed to be the only lung volume to be affected by the presence of inspiratory muscle fatigue. However, and not surprisingly, such small differences in power in the realms of 600W did not prove to be statistically significant. Post-hoc analysis showed that participant numbers needed to be appreciably larger to detect aforementioned differences that could be attributed to fatigue, and provides a strong argument that there was no real difference to detect.

The lack of difference between un-fatigued and fatigued power trials poses a number of interesting questions. As noted earlier, inspiratory muscle fatigue produced significant decrements in static force production in the catch position, which occurs at the beginning of the stroke. However, the influence of inspiratory muscle fatigue appeared to dissipate through the stroke since it was not manifest in a change in power. It has been argued that the posture at the catch places the body in a cramped position (Cunningham, et al., 1975), and that posture has an influence on the compression of the abdominal and thoracic cavities (Wasjwelner, et al., 2000 – cited in Daffertshofer, et al., 2003). This may have an effect on the forces acting on the diaphragm, and place it in an inefficient position at the catch, which may be negated as the body extends throughout the rowing stroke.

It is reasonable to suggest that, given the anthropometry of a rower, flexion of the lower limbs during the recovery phase of the stroke could cause undue mechanical compression on the abdominal and thoracic cavities, resulting in an increase in IAP, placing the diaphragm into an unnatural and inefficient position. This could very well affect the forces being produced at the catch due to the diaphragm's inability to transfer force effectively, and could be exacerbated by the presence of diaphragm fatigue. This is supported by the fact that the influence of IMF was greatest at TLC when IAP would be largest due to the movement of the diaphragm into the abdominal cavity (Figure 11). However, as the legs extend and mechanical compression on the abdominal cavity is released, it is possible that the diaphragm could return to a more efficient position, which enables force and power transmission to be applied more effectively. This could explain why there is no significant reduction in power production, but a significant reduction in force at the catch; however further research is needed to examine the position of the rower at the catch, whether the compression of the abdominal cavity is influenced by the flexion of the legs, and if this influences the position of the diaphragm. Analysis of the internal pressures generated at various parts of the stroke is discussed in a later section.

It should be remembered here that the power measurements were only taken over one stroke; the diaphragm may well be able to cope with the effect of fatigue upon power production for a single stroke, but not during continuous rowing. Future research should investigate the effects of IMF upon force and power production over longer periods of time.

5.5 Analysis of the Self-Selected Lung Volume

In an un-fatigued state, the lung volume spontaneously selected by the athlete was ≈35-40% of TLC. However, this decreased slightly with the influence of IMF to ≈25% of TLC. During maximal rowing, tidal volume increases to approximately 60% of VC. The statistical analysis of the self-selected lung volumes showed that although there was some considerable variation in the lung volume within the force and power trials (≈15%); the differences between these volumes were not statistically different when using paired t-tests with Bonferroni correction. For both force and power, the self-selected lung volume was lower in the fatigued state than in the un-fatigued state. This is to be expected, as it will be less comfortable to inhale deeply when the inspiratory muscles are fatigued.

The self-selected lung volume itself is an interesting notion. This was the volume identified by each participant as the one which they felt to be the most comfortable, or at which they felt they could generate the greatest force or power. This proved to be the case for the un-fatigued force production, as the self-selected lung volume produced the greatest force output (1346N), although this was not significantly different to the highest prescribed lung volume. In contrast, the self-selected force production did not yield the greatest force output in the fatigued state, however, the difference between the S-S result and the highest result from the prescribed lung volumes was not statistically significant. It seems as though for force production, the self-selected lung volume provides somewhere near the greatest force output. Quite the opposite is the case for the power results, where the self-selected lung volume produced some of the lowest results for the power trials.

The self-selected lung volume may not necessarily provide the optimal lung volume for achieving power production, but it may allow the athlete to obtain the most mechanically effective position for obtaining the greatest force production, alternatively it may provide the most comfortable position for the athlete to take the catch. It is possible that these requirements generate different self-selected lung volumes, and that the final volume may be a compromise between the two. This may help to explain the differences in force and power output for similar self-selected lung volumes. The catch position for all of the rowing strokes (both static and dynamic strokes) was not rigorously standardised, and as there was no control over the variation of the catch position, this is a weakness of the study. It is possible that the quality of the data could have been improved had standardisations been in place. This should be attended to in future studies in order to assess the influence of, and possibly determine the most effective catch position.

5.6 External Validity of Lung Volume Attainment

In terms of external validity, the method used to achieve the lung volumes in this study was not ideal, and may influence interpretation of the results. The purpose of the self-selected volume was to see whether athletes were able to spontaneously adopt a volume that gave an optimal force or power output. As it happens, there were not any statistical differences between the self-selected volume and other volumes above RV, so to some extent the self-selected volume is irrelevant. As noted by a number of authors in previous studies (Siegmund, et al., 1999; Bonsignore, et al., 1998; Paterson, et al., 1986; Bechbache & Duffin, 1977; Jasinkas, et al., 1980; Mahler, et al., 1991a, 1991b; Steinacker, et al., 1993), rowers tend to inspire prior to the catch to achieve the pre-drive lung volume, which is thought to stabilise the thorax before the drive phase of the stroke (Biersteker, et al., 1986). The present study used end-expiratory lung volume (EELV) as the method to achieve the self-selected lung volume, (see also 5.10). The self-selected lung volume attained during maximal effort rowing (especially toward the end of a maximal intensity piece of rowing) is not entirely self-selected; it is influenced by a number of external factors such as ventilatory drive, stroke rate (Steinacker et al., 1993), position of the upper body, and compression of the torso by the legs during the recovery phase. None of these factors would have had an influence on the volume selected by the participants in this study, as the specific volume was achieved in the finish position, with no external or internal compressive factors on the torso, and only a single maximal stroke was performed. It is possible that these factors could influence the self-selected volume achieved prior to a rowing stroke, and would need to be taken into account to give a ‘true’ likeness to obtaining S-S volumes during maximal intensity rowing.

5.7 Analysis of Internal Pressure Data

The lower lumbar vertebrae of rowers are subjected to extreme shear and compressive loads during the drive phase of the rowing stroke (Hosea, et al., 1989), therefore the relatively high presence of back injuries (with respect to the low total number of injuries in rowing) should not be surprising (Hosea, et al., 1989; Stallard, 1995; Strayer, 1990

[Stallard & Strayer cited in Manning, et al., 2000]). Previous research has suggested that high intra-abdominal pressure may protect the spine from the detrimental effects of such forces (Norris, 1995; Bartelink, 1957; Morris, et al., 1961; Keith, 1923; Eie & When, 1962 – cited in Manning, et al., 2000; McGill & Norman, 1987; Marras, et al., 1985). More recently, IAP has been found to increase with fatiguing lower back muscles (Essendrop, et al., 2002), further supporting the suggestion. A semi-Valsalva was used in this study, and although full Valsalva manoeuvres facilitate the greatest increase in IAP, however, a full Valsalva would be not compatible with meeting the extreme ventilatory demands of maximal rowing. Notwithstanding this, research has shown that oarsmen and oarswomen manage their ventilatory demands through entrainment of their breathing to the rowing stroke (Steinacker, et al., 1993; Mahler, et al., 1991a; Mahler, et al., 1991b) and IAP has been shown to fluctuate with breathing (Harman, et al., 1988).

Manning, et al. (2000) showed that expiring during the drive brings about higher IAP when compared to inspiring during the drive. This effect presumably reflects the presence of an ‘activated’ [non-compliant] abdominal wall during expiration, whilst during inspiration during the drive, diaphragm descent induces outward movement of the [compliant] abdominal wall. Towards the end of an extended maximal effort piece, such as a 2,000 m race, breathing tends to become very sporadic and entrainment of breathing can break down. Inspiration during the drive can occur in this state, and as the athlete will still be producing large powers and forces, inspiration during the drive will reduce the IAP and spinal stability. This exposes the lower lumbar spine to the increased possibility of lower back injury.

Manning, et al. (2000) also showed that IAP increases with increasing power, 100W to 200W, via 25W increments. Although their study characterises the relationship between power output and IAP, the powers used were very low, and do not represent anywhere near maximal effort rowing. These data therefore fail to give any indication of the pressures that are achieved during maximal rowing, how IAP interacts with ITP, or the level of diaphragm activity during maximal rowing. Manning et al. (2000) reported maximal IAP values of 62.7 mmHg, which equates to 85.3 cmH_2O (1 mmHg = 1.36 cmH_2O). In our pilot experiment, maximal IAP values exceeded 144 cmH_2O. However, there are a number of differences between these two studies that must be acknowledged.

Firstly, the Manning study used 5 participants, none of whom were experienced or competitive oarsmen. Additionally, they were given very little time to familiarise themselves with the rowing ergometer or the mechanics of the rowing stroke. Research has shown that although novice rowers can entrain and control their breathing over an 8-month period (Mahler, 1991a), elite rowers have superior lung function and breathing discipline when compared to novice rowers. Superior breathing control will inevitably have an effect upon the IAP pressure generation, as experience intuitively trains the trunk and abdominal muscles to brace and prepare in order to cope with the demands placed on the trunk and lower spine during rowing. It is likely that the greater power outputs generated by experienced oarsmen would generate larger IAP and explain the difference in IAP between the two studies.

Although IAP is important with respect to lumbar stability, the mechanics of this action are not fully understood. Early research has shown IAP to relieve the loads placed on the lumbar spine (Bartelink, 1959; Keith, 1923; Morris, et al., 1961), however several later studies have failed to show any evidence to support this theory (Bearn, 1961 – cited in Cholewicki, et al., 1999; Krag, et al., 1984, 1985, 1986 – cited in Cholewicki, et al., 1999; McGill & Norman, 1987; Nachemson, et al., 1986; Örtengren, et al., 1981). Although the data from the present study agree with previous research with respect to pressure fluctuation trends (Manning, et al., 2000), they are insufficient to shed any new light on the role of IAP in the relief, or otherwise, of the loads placed on the lumbar spine during the drive. Hosea, et al. (1989) pioneered this field of research, however there has been little quantitative research in this area subsequently. Further research is needed to quantify the effects of IAP, and its relation with lumbar stability under varying rowing conditions.

However, IAP is not an isolated quantity; it must be considered within the context of the entire torso. Thus, several other factors need to be taken into account. IAP is likely to be an important factor with regards to force and power transmission through the body, however, intra-thoracic and trans-diaphragmatic pressures are also likely to play a role in force and power transmission. Early research into ITP indicated that it may have a similar load-relieving effect on the thoracic spine as IAP does to the lumbar spine (Bartelink, 1957; Morris, et al., 1961; Davis & Troup, 1964; Eie, 1966), However, more recent research indicates the same lack of agreement surrounding load-relieving properties as there is with IAP. An additional role of IAP may arise from its effect on opposing rib deformation and thus reducing the risk of rib stress fracture, which is another common injury in rowers.

In addition, since the crural diaphragm inserts onto the upper three lumbar vertebrae; it is reasonable to suggest that the diaphragm may contribute directly to stabilising these vertebrae. The T_{12} vertebra (located at the abdominal/thoracic junction, bearing the 12^{th} rib) has been identified as a mechanically important area for force transmission, therefore the potential effects of ITP and IAP as stabilisers for force transmission around this region of the spine are very important. However, ITP and IAP both have an effect on P_{di}, and consequently, the diaphragm plays an important role in regulating the interrelationship of IAP and ITP.

The present study is the first to monitor ITP, IAP and P_{di} during rowing, specifically a 30-s maximal effort sprint on an ergometer. The maximal effort piece utilised a 1:1 breathing ratio, using a semi-Valsalva manoeuvre during the drive. This semi-Valsalva manoeuvre has been shown to increase IAP to 1.5 times that observed during a Valsalva manoeuvre (Manning, et al., 2000).The figures demonstrated in the Manning study were significantly lower than those found in the present one (144 cmH_2O vs. 85.3 cmH_2O), however, both studies only used one participant to evaluate this phenomenon, which requires further clarification.

With reference to Figures 17 & 17a, the drive can be identified as the point at which ITP stops decreasing. ITP decreases during inspiration, and inspiration stopped immediately prior to the drive. Up until the catch point, IAP increases. This is probably due to the expansion of the thoracic cavity with increasing lung volume and the downward movement of the diaphragm into the abdominal cavity. The trunk muscles may also be contributing to this increased IAP as they will be aiding the 'hip pivot' required to transfer weight onto the footplate of the ergometer in order to obtain good technique, and externally compressing the abdominal cavity by the thighs; external abdominal compression has been shown to increase P_{di} significantly (Hillman, Markos & Finucane, 1990). Additionally, P_{di} increases to its first peak during the preparatory phase for the catch (the recovery). As the drive commences, both IAP and ITP rise quickly, accompanied by a small decrease in P_{di}. These changes come about as the thoracic and abdominal cavities brace, working to overcome the load on the ergometer, and transferring the forces produced through the body to the oar handle.

Interestingly, during the stroke, P_{di} peaks on three occasions, at the catch, the finish, and mid-way through the drive; the latter is probably at the point where the back begins to ‘open up’ and contribute to the force production of the stroke. This suggests a substantial amount of work is being carried out by the diaphragm, or the diaphragm is being subjected to significant opposing forces. Under the conditions of our trial, ventilatory demand was not very high due to the brevity of the maximal effort, so the work of the diaphragm must be contributing to the stabilisation of the torso and controlling the pressures being created in the thoracic and abdominal cavities. The pressures being generated by the diaphragm averaged 59 cmH_2O, peaked in excess of 111 cmH_2O, and ranged over 104 cmH_2O. These figures are surprisingly high, and added to the work of the diaphragm required for maximal ventilation by extended periods of maximal effort rowing, it seems that the diaphragm has to work incredibly hard in order to maintain ventilatory and stabilisation demands.

As mentioned above, P_{di} peaks at three points during the stroke, one of them being the catch position. The debate still ensues over whether the abdominal cavity is compressed at the catch, whether the body is placed in a cramped position, and the effect that this has upon the subsequent stroke. The effects of abdominal compression of transdiaphragmatic pressure have been documented. Hillman, et al., (1990), showed that maximal diaphragmatic inspiratory effort accompanied by external compression increased P_{di} significantly (87 vs. 171 cmH_2O). This also suggests that P_{di} is not a pure index of diaphragm contraction force; it is influenced by external factors and abdominal muscle contraction. What is interesting, however, is that our data shows that the P_{di} value at the catch, where external compression *may* exist, is lower than the P_{di} value at the finish, where no external compression exists (although there is high activation of the abdominal muscles). This gives an interesting insight to any potential compression that may occur at the catch; it does not seem to contribute to the highest P_{di} generated. The compression of the abdominal cavity by the thighs may not have the significance that some authors attribute to it. Unfortunately, the current study only examined the relationship of P_{di} during maximal intensity rowing in an un-fatigued state; it would be very interesting and informative to examine this relationship under whole body fatigue and respiratory muscle fatigue conditions.

Another interesting observation from the pressure traces, was that IAP peaked twice during the stroke. This phenomenon is consistent with IAP traces of Manning, et al. (2000), however the pressures that are generated at these two peaks vary. The pressures generated at the catch are similar, but the second peak at the finish of the stroke differs considerably between the two studies. Whereas Manning, et al., (2000) found finish pressures in the region of 60 cmH_2O, finish pressures in the present study were similar to those found at the catch (145 cmH_2O). This could be explained by technical styles. The present study used an elite level rower, where power is continually applied through the stroke, with an emphasis on the opening of the back contributing to power production late in the stroke. This then emphasises power production towards the end of the stroke, and IAP could well increase to facilitate this. Novice rowers lack this technical ability to continue the application of power throughout the stroke, and tend to finish off the stroke rather poorly, looking to start the recovery quickly to prepare for the next stroke. This lack of power production at the end of the stroke could explain the smaller IAP values in the Manning, et al. (2000) study. Additionally, the elite rowers' posture at the finish of the stroke tends to be very upright and supportive of the torso, whereas this is not evident in novice rowers who tend to slouch and 'sit into themselves'. This postural difference in elite athletes will involve the use of the abdominal muscles and may also affect the IAP found at the finish position.

Research in this area with respect to rowing is severely limited, and further research into the pressures generated in more experienced rowers, with increasing work rate at a set stroke rate, and increasing stroke rate at a set work rate is needed to gain a better understanding of the interaction between ITP, IAP and P_{di}. The functional relevance of this information is extremely valid, as it would shed light on the interrelationships between these pressures, their relationship to force and power production, and also on how these pressures may protect or subject concentrated forces to the spine, and their relation to incidence of injury.

As this is the first study of its kind to monitor multiple internal pressures during rowing, it is difficult to summarise the data that has been produced. The traces produced for IAP seem to tie in with those observed by Manning, et al. (2000), although only by the fact that they describe the trace by stating that IAP peaks twice, as it does in our study. ITP and P_{di} during maximal intensity rowing has not been previously monitored, so there is no comparison, but it is clear that the diaphragm performs an inordinate amount of work, and could be integral to force and power transmission. Unfortunately, none of the pressures were recorded in a fatigued state, so the authors are unable to state what effect IMF has on pressure generation, the interrelationship between these pressures in a fatigued state, or on relieving the spine of shear and torsional loading. Work in this area would shed some light on this problem, and could also provide more information on the mechanisms involved in potential injury prevention.

There was no clear relationship between lung volume and either force, power, or internal pressure generation, certainly nothing as straightforward as a linear or curvilinear relationship. This highlights the large variability of the factors that influence a rowing stroke; torso, hip and knee flexion, drive time, timings of the various phases of the stroke, and many other influences all contribute to force and power output for a particular phase of the stroke, as well as the stroke as a whole. An inherent lack of a consistently executed stroke could help to explain the lack of any trends.

5.8 Anecdotal Feedback

The athletes provided insightful anecdotal feedback during the testing. For example, whilst they were performing the strokes at RV, they commented that they did not feel very 'strong' or comfortable in this position. They also reported that the desire to breathe again was greater than the desire to produce large forces. It was also noted that the athletes felt like the 'lungs wanted to collapse' during the drive phase, and that this was not a comfortable sensation, which resulted in the athlete taking noticeably less time to perform the force strokes at RV than for any other stroke. This is supported by the data in both static and dynamic efforts at RV strokes, which were generally slightly lower in power/force than any other volume.

A similar view was expressed for the TLC strokes; it was noted that the athletes felt as if the lungs were 'too large' and felt a need to expire some of the air to obtain a more comfortable position. It was noted that the chest felt like it wanted to 'explode' under the pressure created during the drive, and hence the athletes felt that they could produce larger forces with slightly less volume in the lungs. It was also mentioned by some of the athletes that the volume of air in the lungs at TLC prevented them from getting into the preferred catch position, and that they felt this limited their force output also. This was not evident in the baseline trials, although this could help to explain the relationship found during the fatigued trial, where higher forces were produced at lower volumes. However, the athlete did not feel 'optimal' performing strokes at TLC, even if this was not reflected in the results.

Feedback from the athletes regarding the self-selected lung volume was very interesting. The athletes felt that they could achieve the most comfortable and optimal position at the catch for them to feel as if they were producing the largest forces during the subsequent drive using this lung volume. This is consistent with the force production results. During the baseline trial the self-selected lung volume produced the largest forces, and during the fatigued trial, the self-selected lung volume matched up well with the volume required to produce the greatest forces. In terms of force production at the catch, athletes did tend to naturally 'self-select' the optimal lung volume for producing the greatest forces in either a fresh or fatigued state. With regards to the power results, the self-selected volume proved to elicit lower power productions when compared to some of the prescribed lung volumes, however the difference was very small and probably meaningless. Although the lung volumes proved to hold no statistical significance , some functional significance could result.

5.9 Limitations

One of the most important limitations to the present study was the low participant numbers. As mentioned previously, this study is the first of its kind, so attempting to ascertain numbers for the study *a priori* proved difficult, and ultimately cost the study statistical power. This being said, similar studies using smaller participant numbers still managed to generate sufficient statistical power to detect the relatively small changes found in their data. Reasons why the present study did not have greater power with its larger sample size can only be put down to the larger inherent variability of the outcome measures.

Another limitation proved to be the time of year when the athletes were tested. Much of the testing occurred just as the winter season had started, and commitment to training was of a high priority for the athletes. Due to the nature of elite level training, and the time frame over which the testing took place, it was near impossible to regulate the rest, recovery or psychological state of the athletes prior to testing. The intensity and application of rowing training varies enormously from day to day, as does the athletes' recovery response to that training, and it is unlikely that the athletes would be in the same physical or mental state before testing on both occasions. Although every effort was made to establish the athletes' training routine and identifying the best days on which to test so that they entered both testing sessions with similar training schedules behind them, this variation inevitably affected the outcome of the results to some extent.

Undoubtedly, the biggest limitation for this study was the inability to measure force and power within the same stroke. The methods used for data capture meant that we were limited to analysing force data during a single static effort, and analysing power with a different stroke. Initially, purpose-built ergometry with dedicated hardware and software (provided by BIRO and built by Imperial College, London, using purpose-written LabView Software) was to be used. This had the benefit of directly monitoring and measuring changes within the ergometer, producing highly reliable data, and the bonus of viewing individual power curves, handle force curves, handle elevation profiles, stroke length profiles and a whole host of other information on a stroke-by-stroke basis. Not only would this method have given us the opportunity to view more detailed stroke data, it would have also given us the possibility of monitoring changes in the profiles of force, power, handle elevation, etc, with changes in lung volume and fatigue state. Unfortunately, the bespoke equipment and software proved to be flawed, and validation work revealed numerous inaccuracies within the analysis software. The equipment was therefore reluctantly changed shortly prior to the commencement of testing. Thus, much of the relevant and additional stroke information that could have been drawn from using the bespoke equipment was no longer available. The use of the alternative equipment also impacted upon the time required to test and analyse the data.

The major limiting factor with the force measurement that was used in the study was that it could only be measured statically, and only at one point in the stroke (the catch). The catch may not be the point in the stroke that yields the highest force output. The limitation of the position of measurement (and the lack of standardisation around the position used in the study) may not yield the 'true' relationship between lung volume and force production, and the ability to measure the force production across the entire stroke is needed in order to ascertain the real relationship.

5.10 Functional Relevance

Although there was no statistically significant influence of lung volume upon either the force or power data, there are some relevant observations to be taken away from this study. Power does not appear to increase with increasing lung volume. The relationship appears to be quite variable with regards the individual athlete; some show quite a linear profile, others more variation. It could be hypothesised that those individuals who produced their greatest power at a particular percentage of lung volume may well share similar breathing strategies and perform better as a crew. In a sport where entrainment of breathing and rhythm of movement plays such a crucial part in determining performance, a small matter such as maximal power output for a certain lung volume could provide that additional fragment of performance enhancement.

Although a lack of statistical power precluded the detection of difference between the lung volumes for the group, there were specific lung volumes for each individual that yielded superior power output. Inter-individual variation for optimal lung volume was no doubt obscured when the whole group was analysed. Although there was no statistical significant difference between any of the lung volumes, this does not mean that there is no functional significance. For example, a 1% difference in performance may not prove to be statistically significant, however, that same difference is functionally very significant to an athlete. Assuming perfect technique, more power per stroke means faster boats, and in a sport where the difference between winning and losing can be a few tenths of a second, every stroke counts. It may be important that every individual ascertains their optimal lung volume and therefore their greatest power output per stroke, and that they adapt their breathing strategy to ensure that this is utilised in training and in competition.

An important functional application of the data can be found in the force data, particularly in respect of the data in the fatigued condition. As described in the Literature Review, rowing requires the application of a large amount of force and power through the oar, and for this force and power to be continuously re-applied for the length of the race. The force applied at the beginning of the stroke is used as the initial ‘pick-up’ of the boat to maintain or increase the boats’ speed. A lack of force at this point of the stroke will result in a decrement in boat speed and performance. Statistically significant differences were found between force produced in fatigued and un-fatigued states, which may have a negative effect upon boat performance. IMF has been documented following competition (Volianitis, 2001a, Griffiths & McConnell, 2007). Respiratory muscle fatigue can occur during any stage of the rowing piece, and can therefore have effects on performance during any stage of the race. Thus, it is reasonable to take steps to minimise the likely impact of IMF upon performance. Specific inspiratory muscle training has been shown to attenuate IMF and improve performance in rowing (Volianitis, 2001b).

In addition, it is clear that respiratory muscle fatigue is likely to influence how the body is stabilised, how efficiently force is transmitted through the body, and potentially how pressure is co-ordinated between the abdominal and thoracic cavities. This last point is of great significance. The influence of respiratory muscle fatigue on thoracic and abdominal stability and force transmission has consequences for the acting upon and through the spinal column. It is possible that inspiratory muscle fatigue may negatively affect susceptibility to lower back injury in rowers, and that intra-thoracic pressure may influence risk of rib fracture. This is an immensely important area with respect to future research, especially as one of Great Britain's high profile rowers was recently subject to combined rib and lung injury, consequently losing a seat in an Olympic boat. Information in this area could have prevented or given light to the potential for this injury.

5.11 Future Direction

Although using a single maximal stroke has its benefits, a more consistent method of achieving maximal continuous rowing, for a greater number of strokes, whilst utilising a particular lung volume (e.g. $25\%_{TLC}$) needs to be devised and applied, as opposed to single strokes used in this study. The problem here is formulating a method where the participant can consistently attain and utilise a particular volume with every stroke. However, this would then give a more reliable range of power output per lung volume over a greater number of strokes, taking variations in technique into account, and therefore a more dependable indication of power at a given lung volume. This could then result in a clearer and more functionally relevant relationship between power or force and lung volume.

Most importantly, the method by which the force and power data is obtained needs to be improved in order to gather accurate information for each stroke, with this information being recorded in such a manner that complex analysis of the data can be achieved and made relatively simple. This analysis would have been possible, had the bespoke equipment identified for use in this study been accurate and reliable. Future research in this area needs to ensure that similar software is available for testing in order to obtain as much stroke information as possible.

The current study piloted some research into the interaction between thoracic, abdominal and trans-diaphragmatic pressures during maximal intensity rowing. This is an entirely new area of research, and this study is the first to explore these interrelations during the rowing stroke. What is immediately striking is the uniformity of the pressure traces for each stroke throughout the short maximal intensity piece. Unfortunately the relationship between pressures and force/power production can only be surmised, but what is known is that the pressures being generated in the pieces are of a considerable size. The interrelationship of ITP, IAP, the resultant Pdi, and the fluctuations of these pressures throughout the stroke have raised many questions.

There is huge potential to gain some significant information with future research in a whole host of avenues. Some of these include pressure maintenance during extended rowing, the co-ordination of the three pressures, the effects of different entrainment ratios, rate or power changes, whole body and respiratory muscle fatigue, and pressure generation on spinal stability. The potential to relieve the spine of compressive, torsional and shear forces, and thereby potentially reduce the risk of spinal injury is of great interest and significance. Spinal forces have been previously measured in rowing (Hosea, et al., 1989), but the influence of internal pressures on these forces in unknown. Information of the above factors could reduce the relatively high incidence of spinal injuries in rowing present today. The avenues discussed here are only answerable by further study and more advanced data collection methods.

The current study only observed the relationship between intra-thoracic, intra-abdominal and trans-diaphragmatic pressure during maximal intensity rowing. Little research has been completed investigating the effects of work rate, stroke rate and fatigue on the pressures generated during sub-maximal rowing, and the inter-relation between these pressures as work and stroke rates increase. This could also provide invaluable information with respect to spinal loading, spinal stability, and the work of the diaphragm

Further important information with regards the pressure traces could come from characterising the interrelationships between IAP, ITP and Pdi and their changes throughout the stroke. This could help to shed light upon why some individuals are more prone to spinal or rib stress injuries than others, and how breathing techniques or strategies may influence these pressures in an injury prevention context. The pressure traces could be very individual, or heavily technique orientated; this is unknown at present. Differing styles of rowing could also be analysed (e.g. Canadian back over-extension at the finish Vs. English upright positions), giving influences of technique on internal pressure generation and the potential for injury prevention.

Related to the previous point, future research comparing pressure generation between those individuals who have suffered spinal injury/rib stress injuries/low back pain sufferers in rowing, with those who have not, could shed light on why some individuals are more susceptible to lower back injury, or rib stress fractures than others. Individuals that are unable to produce particular pressures in either the thoracic or abdominal cavities at given times or points during the stroke, and the influence of the diaphragm may make some rowers more susceptible to injury than others.

It is also worth mentioning here that this study, although it encompassed heavyweight and lightweight rowers, it only included men. It would be very worthwhile, and provide a greater knowledge base regarding the subject matter, if a repeat of the study was performed on a group of rowers that included female athletes, or by testing female athletes as a group of their own. It is known that women have a greater relative sitting height to that of men; is very likely that the pressures generated, the interrelation of these pressures, and the ability of transmit forces effectively through the trunk may differ to male athletes. However, all of the areas mentioned above are worthy of future research.

Chapter 6: Conclusion

There appears to be little systematic effect of lung volume upon force or power production above $25\%_{TLC}$; however, when the inspiratory muscles are fatigued, there is a systematic effect of fatigue on static force production in the catch position, but not power produced during an entire stroke. It is important to view the data with respect to sample size and statistical power; the absence of a significant effect of lung volume upon force and power production may to some extent be due to insufficient statistical power. Larger participant numbers would probably only make the effect size at RV significant, other differences between volumes were small and unlikely to be 'real'.

This study has also shed light on the relationships between intra-thoracic, intra-abdominal and trans-diaphragmatic pressures during maximal rowing, and has highlighted several important areas worthy of future study, with potentially significant positive repercussions with respect to spinal and rib injuries.

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RESEARCH PARTICIPANT STUDY INFORMATION

Title of Study: Characterising the influence of lung volume upon force production in rowing

Study Investigators: Mr. Adam Gibbs BSc (Hons), Prof. Alison McConnell

Name of Participant:___________________________________

Summary

It has been shown in a number of studies that rowers adapt their work of breathing so that is synchronised with the stroke rate they are performing at. This is called *entrainment*. Entrainment varies in ratio (breaths:stroke) from 1:1 (one complete breath per stroke) to 3:1. It has also been noted in a recent study that rowers tend to inspire immediately prior to the catch, altering the volume of air in the lungs. The aim of this investigation is to establish what influence the volume of this breath has upon the force that is produced in the consequent stroke.

If you decide to participate in this study, your commitment will be spread over 2 to 4 weeks and will require 3 visits to the laboratory located at Brunel University, Uxbridge, West London. Each visit should take between 1-2 hours of your time. During the first visit, you will be shown the equipment, have your lung function assessed, and perform a number of maximal inspiratory and expiratory manoeuvres. Additionally, you will also have some electromyographic recordings (EMG; recordings of muscle activity) of a number of muscle groups taken, which will require maximal voluntary contraction of that particular muscle. The muscles to be investigated are the diaphragm, external intercostals, internal and external obliques, erector spinae group, the muscle group at T_{12} level, rectus abdominis and quadriceps. During this first visit, you will also be required to perform a number of maximal dynamic and static strokes at given percentages of lung volume. The second and third visits involve fatiguing sessions, which will fatigue the respiratory muscles (Respiratory Muscle Fatigue; RMF). This requires you to breathe against a resistive load. A selected number of lung function properties will be measured after each fatiguing session. These measurements will have already been performed during the first visit.

You have been invited to participate in this investigation as one of 25 healthy subjects. Participation in this investigation is entirely voluntary, and you may refuse to start and/or finish at any time.

What will my participation involve?

Visit 1.

Firstly, muscular activity will be recorded using electromyography (EMG). This involves placing two surface electrodes (on the skin) at certain positions on the body to measure the activity of a particular muscle or muscle group under that location whilst performing a task. All EMG activity will be recorded before, during and after maximal voluntary contractions (MVC), where you will attempt to contract a particular muscle or muscle group as much as possible. Two MVC manoeuvres are performed by maximal effort breathing, which determines your inspiratory and expiratory muscle strength by measuring maximal inspiratory pressure (MIP) and maximal expiratory pressure (MEP). This requires a mouth pressure meter (MPM). This is a small, hand-held device, which is placed in the mouth. It significantly reduces the flow of air into the mouth, and records the pressure created during inspiration or expiration. Additionally, a test of lung function will be performed - a maximal flow-volume loop (MFVL). This involves breathing in to total lung capacity (TLC), then maximally expiring until your lungs are completely empty (residual volume; RV), then inspiring with maximal effort to TLC. These tests will be performed several times, until we obtain your best effort.

The second part to the first visit also involves maximal inspirations at percentages of your lung volume. You will breathe through a mouthpiece, which is connected via a number of tubes to a computer which measures and analyses your air and its flow loops, and will provide online feedback which you will be able to view. To obtain the lung volumes needed, you will expire to RV, then be guided (as well as you being able to see) as to how much you will inspire. Once this volume had been achieved, you will inspire with maximal effort using the MPM. Throughout this second part, some maximal expirations will also be performed, also using the MPM. These are all performed from TLC, and also require maximal effort.

The third part to the visit will involve work on the rowing ergometer. Using the same procedures as in the second part, various percentages of lung volume will be achieved, and maximal dynamic strokes on the ergometer will be performed. This procedure will then be repeated, but the ergometer handle will be restrained so that maximal static strokes are performed. EMG activity of all muscle groups will be recorded during all strokes.

Visit 2.

This visit will involve sessions whereby your respiratory muscles will be fatigued. This will occur by using a modified version of a device called a POWERbreathe™, which uses a spring-loaded valve to restrict airflow. This resistance to airflow will create a constant pressure, which will be set at a given percentage of your MIP. You will breathe in time with a computer-generated template that will be clearly visible during the session, until you can no longer match your efforts to the template. Immediately after the fatiguing sessions, a number of maximal strokes and lung function measurements will be taken in the fatigued state. It should be noted that all of these measurements will have been performed prior to these fatiguing sessions, and you should be used to performing them at this stage.

Are there any risks?

There are no known risks with using any of the equipment that will be used during this investigation. However, you may experience some sensations associated with maximal respiratory work, which may include temporary fatigue, shortness of breath, dizziness, and muscle soreness. These sensations are completely normal for the intensity and duration of this type of test, and should be no different to those sensations experienced during any other maximal breathing efforts. These sensations should last no longer than a few minutes after the end of the test.

Are there any benefits?

No direct benefit is expected to occur as a result of participation in this study, but the results of the study are for the greater good of rowing. The results of any testing and/or results of the investigation will be given to you upon request.

Are there any costs?

There are no costs associated with participation in this investigation, bar that of travelling costs to and from the University for laboratory visits. Unfortunately, there are no funds available, therefore you will not be paid for your participation in this study, or reimbursed for any costs associated with travel to the University.

Are there any additional procedures?

Yes, there is the possibility of an additional procedure, which would involve a maximal effort piece on the ergometer. However, it is expected that only a small number of participants would be asked to perform this additional testing, as only the participants that have agreed to have oesophageal balloons passed into them would be asked to perform. These balloons monitor internal pressure and the differences in pressure created by changes within the body (i.e. lung volume). Measuring internal pressures created by changes in lung volume give an indication to how much stability is being ‘created’ for the lower back. This could give light to aspects of lower back injury and prevention.

If a participant has agreed to accept the balloons for the normal stages of this investigation, it would be very beneficial and informative to the rowing world to perform some additional maximal effort work on the ergometer, as there is currently no information on this topic available.

If I decide to start the study, can I change my mind?

Your decision to participate in this study is entirely voluntary. You can choose not to participate in any capacity. If you do decide to participate, you may change your mind at any time without penalty or loss of benefits that you may have had prior to the study. You will be told of any new and significant findings, which may affect your willingness to continue.

Will my identity be protected?

The researchers might use information learned from this study in scientific journal articles or in presentations. All records will be coded to help protect your confidentiality. The data will be stored for an indefinite period of time at Brunel University and will not be released without written permission or unless required by law.

What if I have some more questions?

If you have questions about this research, please contact the main study investigator, Mr. Adam Gibbs on (01895) 266500.

My signature below indicates that I have read the information in this document and have had an opportunity to have my questions answered.

____ __________________

Participant Signature **Date**

____ __________________

Investigator/ Consent Obtainers' Signature **Date**

Brunel UNIVERSITY WEST LONDON

HEALTH QUESTIONNAIRE

Name: ______________________________________

Date of Birth: ____-____-____________; __________(years)

Address: ______________________________________

____

____

____

Phone: ______________________________________

Name of Investigator Responsible for study: ___________________________

Please answer the following questions. If you have any doubts or difficulties with the questions, please ask the investigator for guidance. These questions have been constructed to determine your suitability for the proposed investigation. Your answers should be as honest as possible, all of which will be kept strictly confidential.

Please indicate the last time you saw your doctor: _____________________

	Please Tick YES	NO
Are you female?		
If yes, to your knowledge, are you pregnant?		
Are you currently taking any medication?		
Has a doctor ever advised you not to take part in vigorous exercise?		
Do you, or your family, have a history of heart problems?		

Do you, or your family, have a history of high blood pressure?		
Have you ever taken medication for blood pressure or heart related problems?		
Do you feel chest pain when you undertake physical activity?		
In the last month, have you ever had chest pains when not performing physical activity?		
Has your doctor (or anyone else) stated that you have high blood cholesterol?		
Have you had a cold or fever related illness in the last month?		
Do you ever lose balance because of dizziness?		
Do you ever lose consciousness resulting from physical activity?		
Do you suffer from asthma?		
Do you have any joint or bone problems that may be made worse through physical activity?		
Has your doctor (or anyone else) stated that you have diabetes?		
Have you ever had viral hepatitis?		
Have you ever broken, or have had reconstructive surgery upon, your nose?		
Have you ever had any nasal related breathing difficulties?		
Do you know, for *ANY* reason not already mentioned, why you should not participate in physical activity?		

Are you accustomed to vigorous physical activity (lasting approximately one hour, at least 3 times per week)		
Would you be willing to allow the investigators to insert balloon tipped catheters into your stomach and windpipe?		
Do you currently have, or ever have had any lower back injuries?		

If yes, please give details (type of injury, occurrence, severity, etc...):

____
____
____
____
____
____
____

I have completed the health questionnaire to the best of my knowledge, and any questions I may have had have been answered fully, and to my satisfaction.

______________________________ ______________
Participant Signature **Date**

______________________________ ______________
Witness' Signature **Date**

Brunel UNIVERSITY WEST LONDON

RESEARCH PARTICIPANT CONSENT FORM

	Please Tick YES	NO
Have you read the Research Participant Study Information sheet?		
Have you had the opportunity to ask questions and discuss this study?		
Have you had satisfactory answers to all any questions you have asked?		
Do you understand that you will not be referred to by name in this study or any report concerning this study?		
Do you understand that you are free to withdraw from this study…		
…at any time?		
…without having to give reason for withdrawal?		
…(where relevant) without affecting future participation?		

Who have you spoken to regarding the study? ………………………………………..

Do you agree to take part in this study?		

______________________________ ________________

Participant Signature **Date**

Witness Statement

I am satisfied that the above-named individual has given informed consent.

______________________________ ______________

Witness' Signature **Date**

ERGOMETER WARM-UP/LACTATE PROTOCOL

2k Ergo Score	Starting Watts (W)	Rate	Step 1 18	Step 2 20	Step 3 22	Step 4 24	Step 5 26	Step 6 28
07:15.0	125	Watts	125	150	175	200	225	250
		500m	02:21.0	02:12.7	02:06.0	02:00.5	01:55.8	01:51.8
	130	Watts	130	155	180	205	230	255
		500m	02:19.2	02:11.2	02:04.8	01:59.5	01:55.0	01:51.1
07:07.5	135	Watts	135	160	185	210	235	260
		500m	02:17.4	02:09.8	02:03.7	01:58.5	01:54.2	01:50.4
	140	Watts	140	165	190	215	240	265
		500m	02:15.8	02:08.5	02:02.6	01:57.6	01:53.4	01:49.7
	145	Watts	145	170	195	220	245	270
		500m	02:14.2	02:07.2	02:01.5	01:56.7	01:52.6	01:49.0
07:00.0	150	Watts	150	175	200	225	250	275
		500m	02:12.7	02:06.0	02:00.5	01:55.8	01:51.8	01:48.3
	155	Watts	155	180	205	230	255	280
		500m	02:11.2	02:04.8	01:59.5	01:55.0	01:51.1	01:47.7
06:52.5	160	Watts	160	185	210	235	260	285
		500m	02:09.8	02:03.7	01:58.5	01:54.2	01:50.4	01:47.0
	165	Watts	165	190	215	240	265	290
		500m	02:08.5	02:02.6	01:57.6	01:53.4	01:49.7	01:46.4
	170	Watts	170	195	220	245	270	295
		500m	02:07.2	02:01.5	01:56.7	01:52.6	01:49.0	01:45.8
06:45.0	175	Watts	175	200	225	250	275	300
		500m	02:06.0	02:00.5	01:55.8	01:51.8	01:48.3	01:45.2
	180	Watts	180	205	230	255	280	305
		500m	02:04.8	01:59.5	01:55.0	01:51.1	01:47.7	01:44.6
06:37.5	185	Watts	185	210	235	260	285	310
		500m	02:03.7	01:58.5	01:54.2	01:50.4	01:47.0	01:44.1
	190	Watts	190	215	240	265	290	315
		500m	02:02.6	01:57.6	01:53.4	01:49.7	01:46.4	01:43.5
	195	Watts	195	220	245	270	295	320
		500m	02:01.5	01:56.7	01:52.6	01:49.0	01:45.8	01:43.0
06:30.0	200	Watts	200	225	250	275	300	325
		500m	02:00.5	01:55.8	01:51.8	01:48.3	01:45.2	01:42.4
	205	Watts	205	230	255	280	305	330
		500m	01:59.5	01:55.0	01:51.1	01:47.7	01:44.6	01:41.9
06:22.5	210	Watts	210	235	260	285	310	335
		500m	01:58.5	01:54.2	01:50.4	01:47.0	01:44.1	01:41.4
	215	Watts	215	240	265	290	315	340
		500m	01:57.6	01:53.4	01:49.7	01:46.4	01:43.5	01:40.9
	220	Watts	220	245	270	295	320	345
		500m	01:56.7	01:52.6	01:49.0	01:45.8	01:43.0	01:40.4
06:15.0	225	Watts	225	250	275	300	325	350
		500m	01:55.8	01:51.8	01:48.3	01:45.2	01:42.4	01:39.9
	230	Watts	230	255	280	305	330	355
		500m	01:55.0	01:51.1	01:47.7	01:44.6	01:41.9	01:39.5
06:07.5	235	Watts	235	260	285	310	335	360
		500m	01:54.2	01:50.4	01:47.0	01:44.1	01:41.4	01:39.0
	240	Watts	240	265	290	315	340	365
		500m	01:53.4	01:49.7	01:46.4	01:43.5	01:40.9	01:38.5
	245	Watts	245	270	295	320	345	370
		500m	01:52.6	01:49.0	01:45.8	01:43.0	01:40.4	01:38.1
06:00.0	250	Watts	250	275	300	325	350	375
		500m	01:51.8	01:48.3	01:45.2	01:42.4	01:39.9	01:37.7

CALCULATIONS OF ETA SQUARED FOR ANOVA

& PAIRED SAMPLES T-TEST STATISTICAL ANALYSES

ANOVA

$$\text{Eta squared} = \frac{\text{Sum of squares between-groups}}{\text{Total sum of squares}}$$

E.g. Between-Groups Pressure-Volume Data

$$\text{Eta squared} = \frac{102579.0}{125171.8}$$

$$= 0.82$$

Paired-Samples T-Test

$$\text{Eta squared} = \frac{t^2}{t^2 + N - 1}$$

E.g. Between-groups force data (RV and 25%)

$$\text{Eta squared} = \frac{-3.097^2}{-3.097^2 + 7 - 1}$$

$$= \frac{9.591}{15.591}$$

$$= 0.601$$

ACCEPTABILITY & REPRODUCIBILITY CRITERIA FOR FVC MANOEUVRES

Acceptability Criteria

Individual spirograms are ‘acceptable’ if:

1. They are free from artefacts
Cough or glottis closure during 1st second of expiration
Early termination or “cut-off”
Variable effort
Leak
Obstructed mouthpiece

2. Have good starts
Extrapolated volume less than 5% of FVC or 0.15l, whichever is GREATER, ***or***
Time to PEF < 120 ms (optional)

3. Have satisfactory exhalations
6 s (10 s is optimal) of exhalation and/or plateau in volume-time curve, ***or***,

Reasonable duration or plateau in volume-time curve, ***or***,
If that subject cannot/should not continue to exhale

Reproducibility Criteria

After [at least] three acceptable spirograms have been obtained, the FVC measures will be deemed ‘reproducible’ if the two largest FVC ***and*** $FEV_{1.0}$ measures are within 0.2 l of each other. If both of these criteria are met, the testing may be concluded. If not, continue testing until:

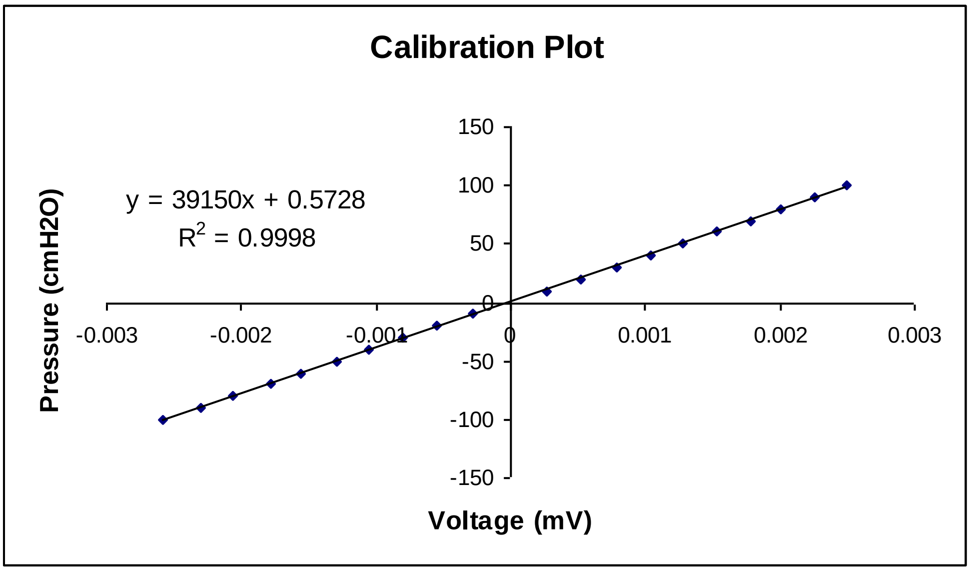
Both criteria are met with analysis of additional acceptable spirograms, ***or***,
A total of 8 tests have been performed, ***or***,
The subject cannot/should not continue.

Save [as a minimum] the three best manoeuvres.

CALIBRATION OF PRESSURE TRANSDUCER

& CONVERSION FACTOR

'Breathing' Out (Positive flow)		'Breathing' In (Negative flow)	
cmH_2O	**mV**	**cmH_2O**	**mV**
10	0.000273	-10	-0.00028
20	0.000523	-20	-0.00055
30	0.000786	-30	-0.00080
40	0.001045	-40	-0.00106
50	0.001282	-50	-0.00130
60	0.001537	-60	-0.00155
70	0.001775	-70	-0.00179
80	0.002008	-80	-0.00206
90	0.002257	-90	-0.00231
100	0.002494	-100	-0.00259



Bland & Altman Test-Retest Data for Ergometer Power, Load Cell Force & Participants' MIP & MEP Measures

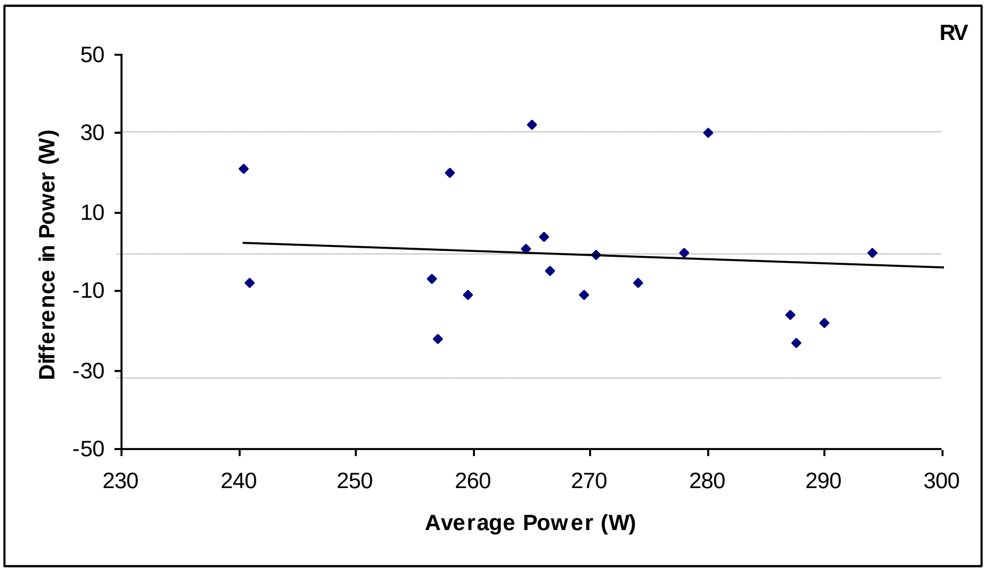


Figure H$_1$. Bland & Altman plot for the RV lung volume (Power)

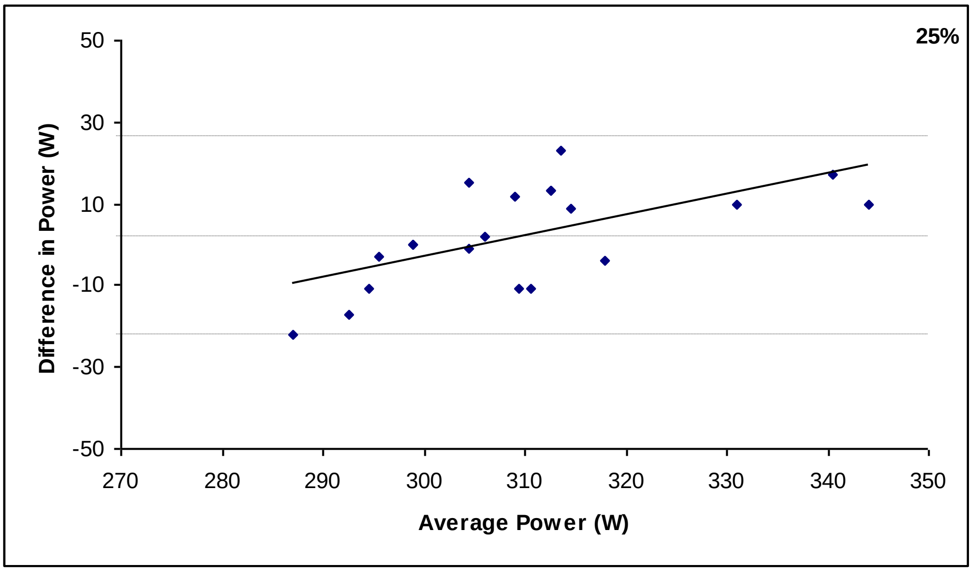


Figure H$_2$. Bland & Altman plot for the 25% lung volume (Power)

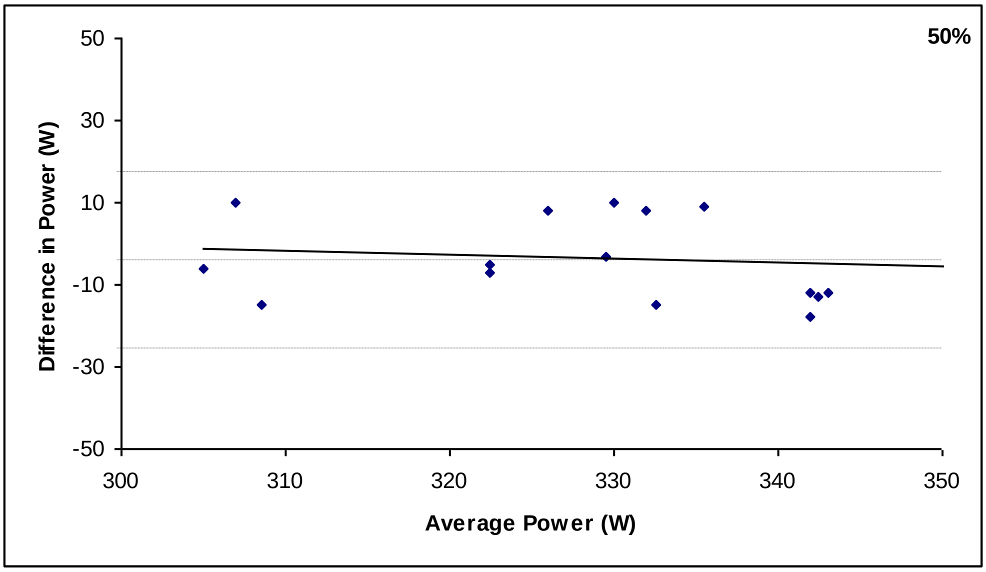


Figure H$_3$. Bland & Altman plot for the 50% lung volume (Power)

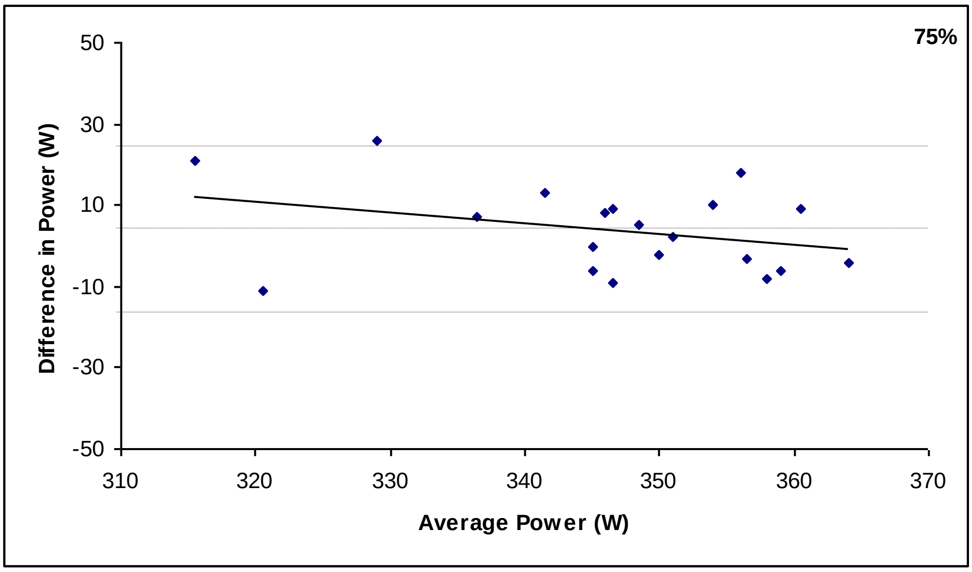


Figure H$_4$. Bland & Altman plot for the 75% lung volume (Power)

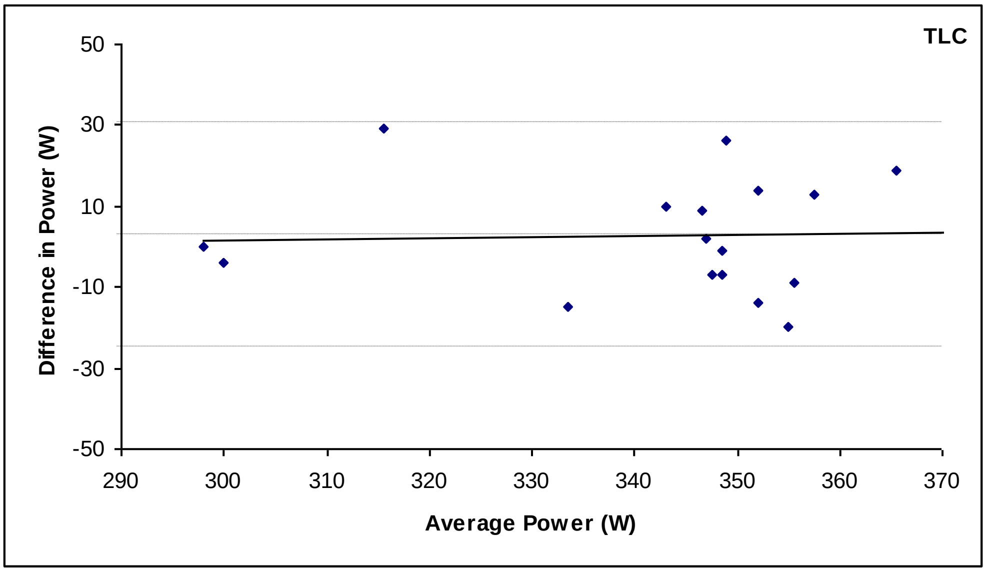


Figure H$_5$. Bland & Altman plot for the TLC lung volume (Power)

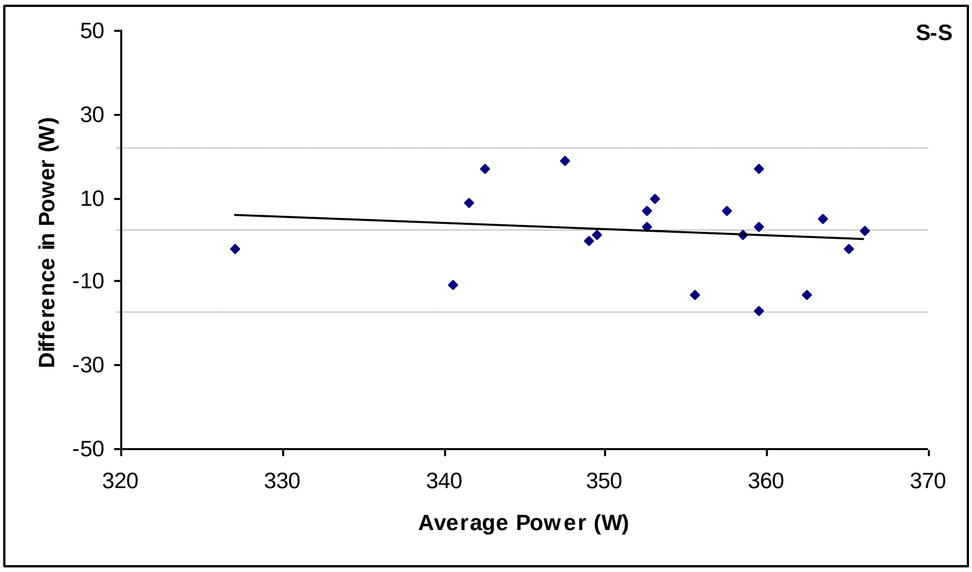


Figure H$_6$. Bland & Altman plot for the self-selected lung volume (Power)

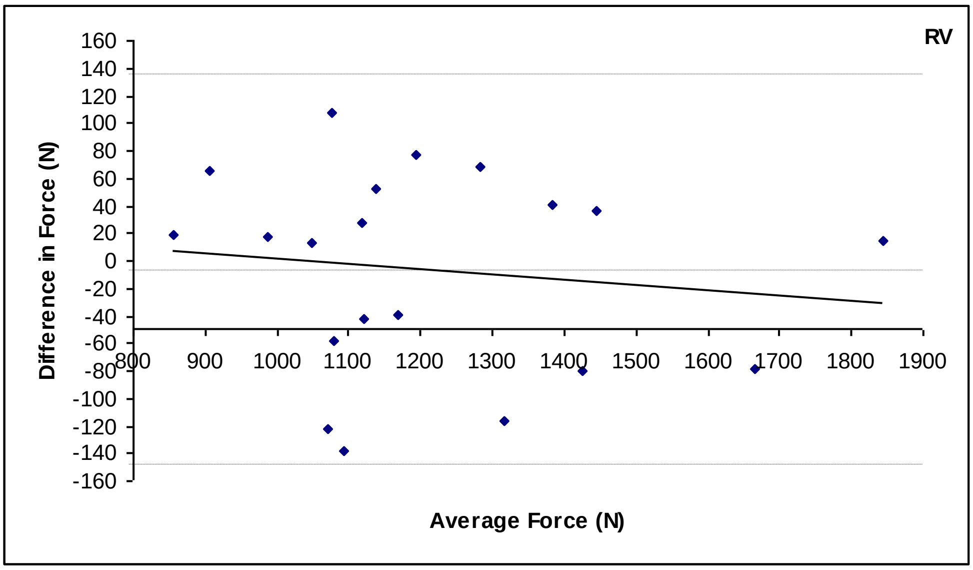


Figure H$_7$. Bland & Altman plot for the RV lung volume (Force)

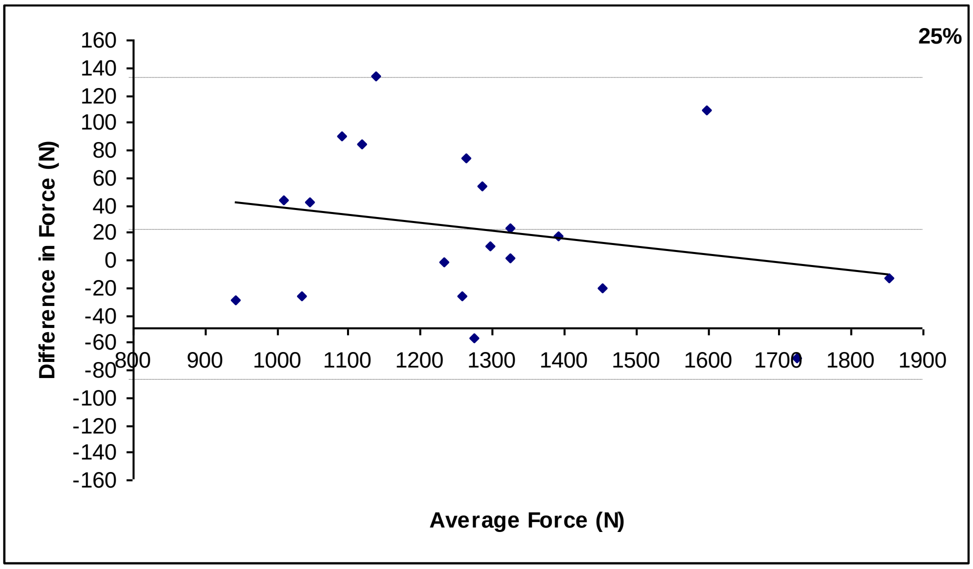


Figure H$_8$. Bland & Altman plot for the 25% lung volume (Force)

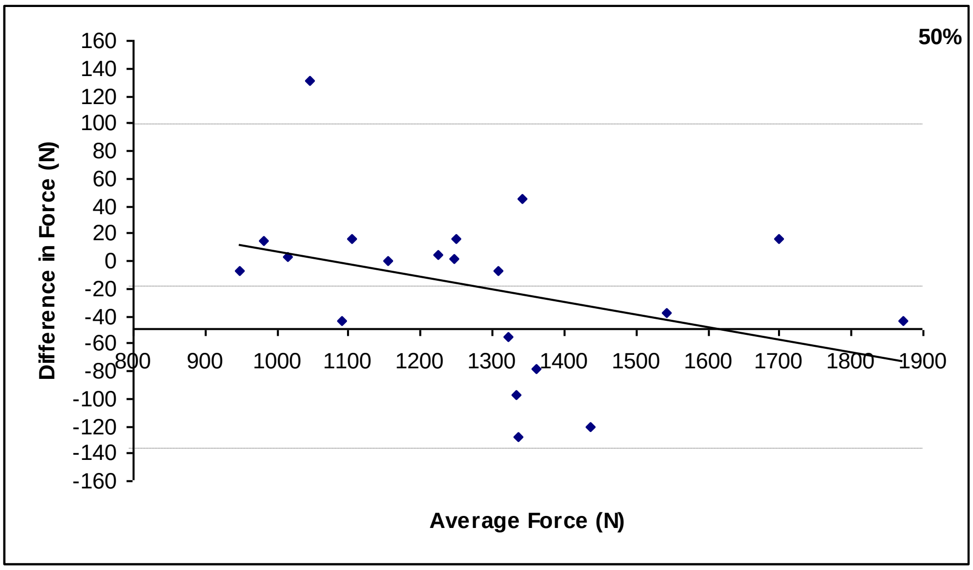


Figure H_9. Bland & Altman plot for the 50% lung volume (Force)

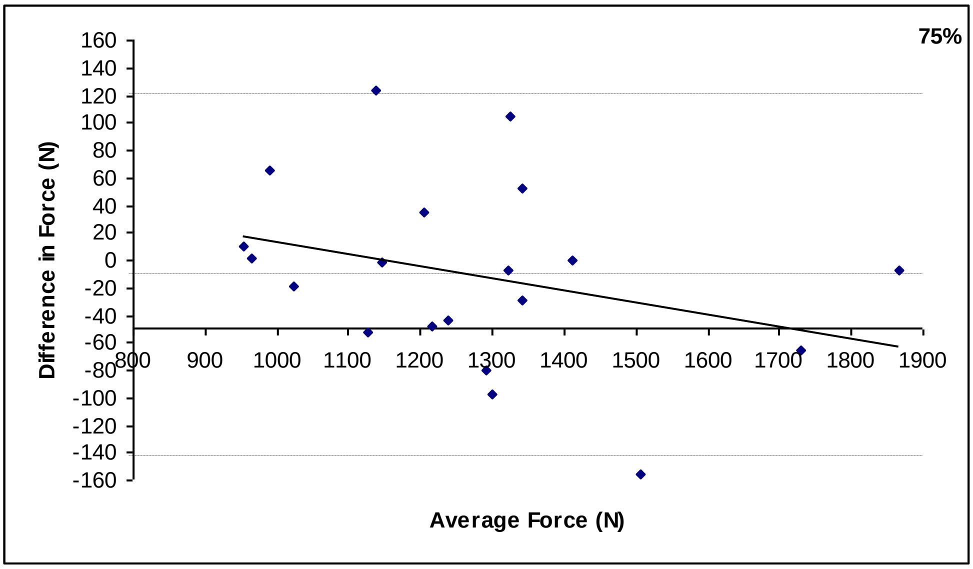


Figure H_{10}. Bland & Altman plot for the 75% lung volume (Force)

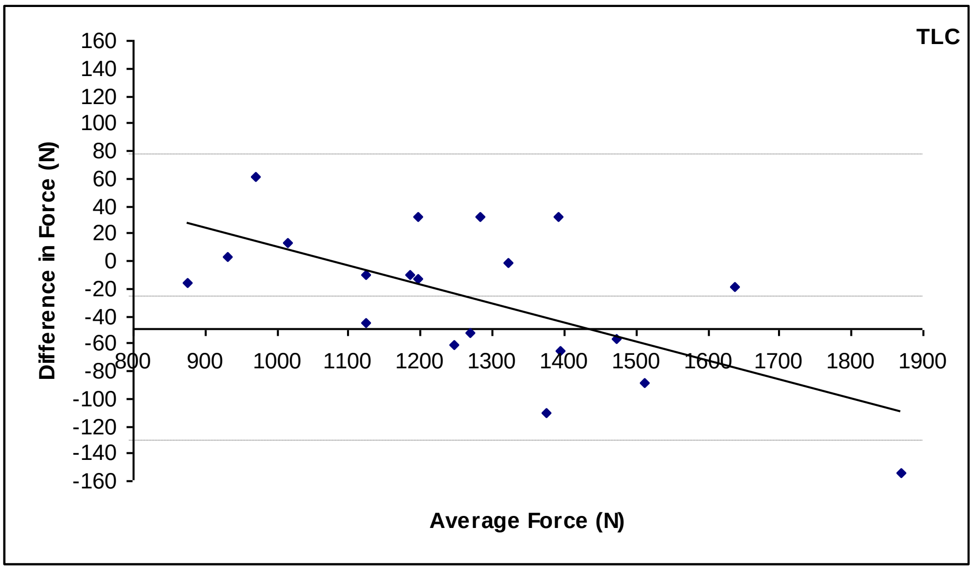


Figure H$_{11}$. Bland & Altman plot for the TLC lung volume (Force)

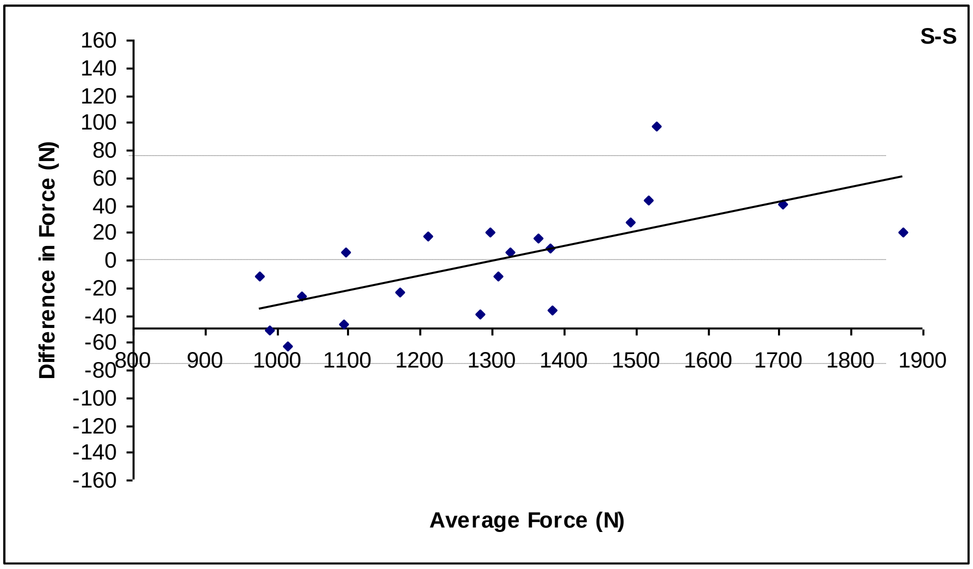


Figure H$_{12}$. Bland & Altman plot for the self selected lung volume (Force)

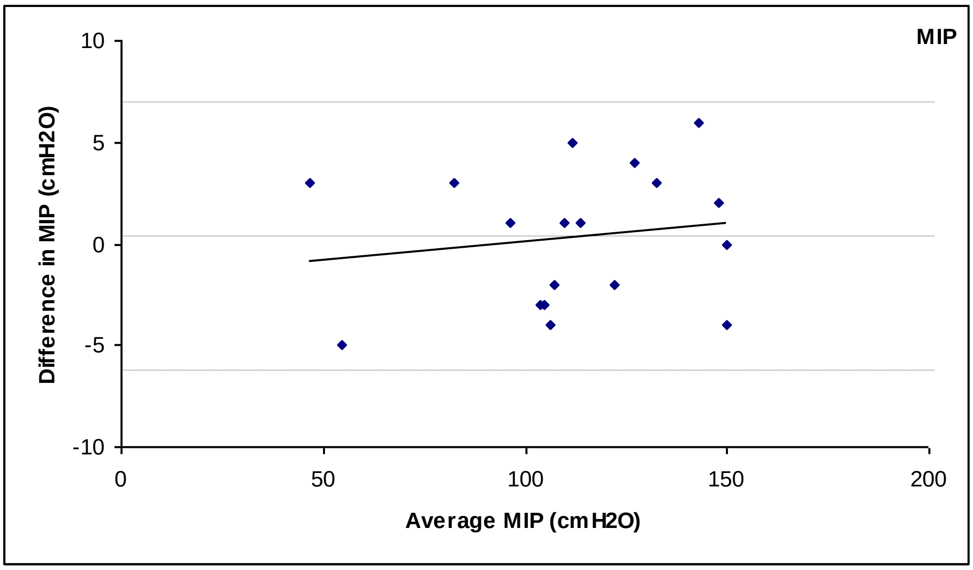


Figure H_{13}. Bland & Altman plot for the MIP trials

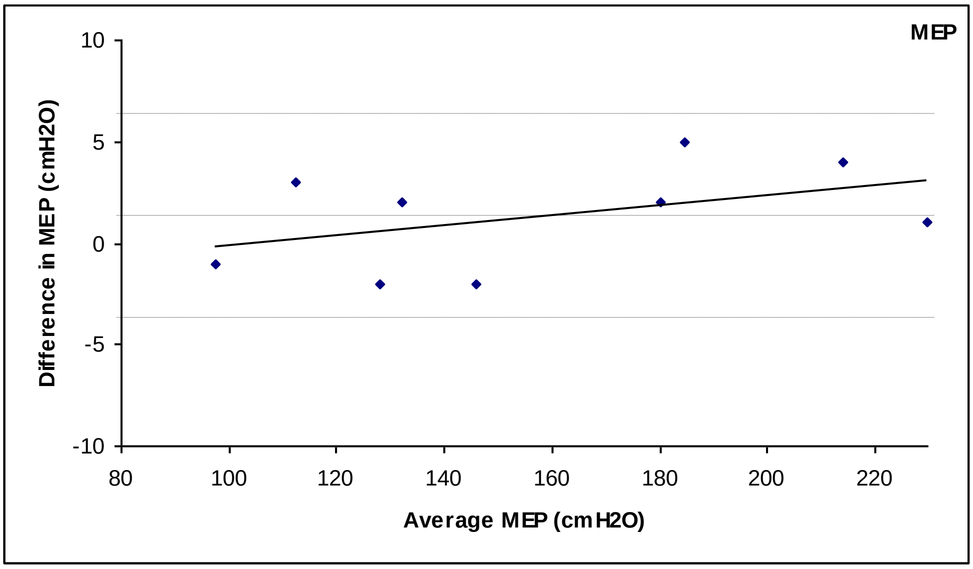


Figure H_{14}. Bland & Altman plot for the MEP trials

Explanation of Figures

The figures above represent the results from the Bland & Altman 'Limits of Agreement' tests that were performed on the data resulting from the study. The Bland & Altman plot is a statistical method usually used to compare two measuring techniques, although in this study it has been used to assess the reliability of measuring apparatus. It produces a graphic, which shows the differences between two measures plotted against the average of the two measures. There are also 3 horizontal lines plotted to represent the mean difference, and the mean difference ±1.96 times the standard deviation of the difference. The Bland & Altman plot is useful to reveal a relationship between the differences and the averages, to look for any systematic bias, and to identify possible outliers. If there is a consistent bias, it can be adjusted for by subtracting the mean difference from the new method. If the differences within the mean ± 1.96 SD are not clinically important, the two methods may be used interchangeably, or the measure can be deemed reliable.