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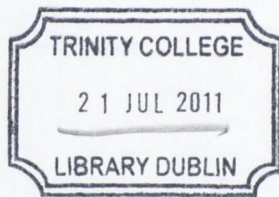
**LUMBAR SPINE INJURY IN ROWING; THE INFLUENCE OF
SPINAL KINEMATICS, ROWING MODE AND FATIGUE.**

Fiona Wilson

A dissertation submitted for the degree of Doctor of Philosophy.

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Discipline of Physiotherapy,
School of Medicine*

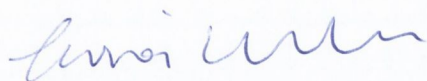
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Declaration.

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Fiona Wilson

15th September 2010.

Summary

Rowing is a sport which requires high volumes of training to compete at elite levels. Studies over recent years have noted an increase in the number of lumbar spine injuries reported by this population; however limitations in data reported to date means that the exact extent of this problem and the associated factors, are not well understood. Therefore, the overall aim of this study was to determine if lumbar spine injury is a specific problem in rowers and to establish how kinematic variables of the lumbar spine relate to this.

Study 1 was a 12 month prospective cohort study of injury in international rowers. It established an injury incidence of 3.67/1000 hours and this was higher than previously reported in a prospective study at 1.5/1000 hours or in the most recent (retrospective) study of international rowers at 2.1/1000 hours. When the injury incidence was put in the context of other sports such as boxing which has a similar competition to training time ratio, the incidence in rowing was high (boxing reported as 2/1000 hours). The most common reported injury in rowers was to the lumbar spine (31.8% of all reported injuries) which was sustained by 65% of the cohort over a twelve month period. The factor that was most significantly associated with injury risk was ergometer training. Those rowers who sustained a lumbar spine injury, did significantly more ergometer sessions during the 12 month period of the study than those who did not ($P=0.049$).

Study 2 examined lumbar spine kinematics in rowing, comparing those in a boat with an ergometer. Kinematics were assessed in the frontal plane as it was expected that this was the plane where the greatest difference between the ergometer and the boat may be observed. The study found that angular displacement of the lumbar spine in the frontal plane was greater on the ergometer (mean of 5°) compared to the boat (mean of 3.4°) and that angular displacement could reach as high as 8.8° . Thus a considerable range of motion was found in the frontal plane which was not in agreement with a previous study which suggested that no movement took place in this plane.

Study 3 examined the effects of a fatiguing protocol on the frontal plane angular displacement in the lumbar spine as study 2 had noted an increase over the course of the rowing trial. On this occasion, rowers completed a physiological step test on the ergometer only, as the greatest angular displacement had been noted on the ergometer in the previous study. The mean angular displacement in the frontal plane at L3 ranged from 4.8° to 7.8° for the four subjects. While all subjects showed an increase in displacement over the

course of the test, those who showed a statistically significant increase had completed more steps and may have been more fatigued. To introduce an assessment of fatigue, the protocol was repeated in study 4 when blood lactate accumulation was measured. Study 4 found a mean increase in frontal plane angular displacement over the course of a step test of 4.1° (1.9) which was statistically significant ($P=0.000014$). While blood lactate concentration also increased incrementally in parallel with angular displacement, it was found that only stroke rate was a significant predictor of increasing frontal plane angle. This suggested that further parameters need to be measured to confirm that the changes were due to fatigue.

Studies 2, 3 and 4 provided information regarding the frontal plane which had not been examined previously and showed that angular displacement in the lumbar spine reached maximum voluntary range established in previous normative data. Although the sagittal plane motion in the lumbar spine of rowers had been examined previously on an ergometer, it had not been done in a boat and this led to study 5. The final study (study 5) examined sagittal plane kinematics in the lumbar spine, comparing lumbar spine motion in the boat with the ergometer. There was an increase in maximum lumbar spine sagittal flexion over the course of a step test protocol, increasing by a mean of 4.4° (0.9) on the ergometer and increasing by a mean of 1.3° (1.1) in a boat. The increase was significantly greater on the ergometer compared to the boat ($P=0.035$). When the mean maximum lumbar spine flexion was compared to the peak standing voluntary flexion (measured pre-test), it was a mean of 11.2% (15.2) greater at the end of the ergometer test and a mean of 4.1% (10.2) greater at the end of the boat test. This showed that the increase in sagittal plane lumbar flexion was significantly less over the course of a boat trial than an ergometer trial.

In summary, rowers are at risk of lumbar spine injury and this risk may be increased with exposure to ergometer training compared to boat training. Both ergometer and boat rowing are associated with high values of angular displacement in the lumbar spine, in both the frontal and sagittal plane which are comparable to those noted as the full maximum voluntary range in previous studies. Lumbar spine angular displacement increases over the course of a rowing trial which may be as a result of fatigue.

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Thank you to my supervisors Dr Ciaran Simms and Dr John Gormley for your support and guidance over the last few years. It has been a complicated process at times and I have always valued your input and faith in me.

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This work is dedicated to the memory of Jimmy O'Toole who passed away at the last stage of my testing. His love of rowing and pride in his family's achievements were very obvious. We all miss his positive spirit. I know that he would have been proud of me for getting to the end!

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LIST OF ABBREVIATIONS

| | |
|----------------------|--|
| BLa: | Blood lactate. |
| BMD: | Bone mineral density. |
| Bpm: | Beats per minute. |
| C2: | Concept 2 rowing ergometer. |
| CLBP: | Chronic low back pain. |
| cm: | Centimetres. |
| CT: | Computerised tomography. |
| EGM: | Electrogoniometer. |
| EMG: | Electromyography. |
| FISA: | Federation Internationale des Societes d'Aviron. |
| IARU: | Irish Amateur Rowing Union. |
| Kg: | Kilogramme |
| Km: | Kilometre |
| Lsp: | Lumbar spine. |
| m: | Metres. |
| MPF: | Mean peak flexion. |
| MRI: | Magnetic resonance imaging. |
| MVC: | Maximum voluntary contraction. |
| OBLA: | Onset of blood lactate accumulation. |
| PSF: | Peak standing flexion. |
| RR: | Relative risk. |
| s: | Seconds |
| SIJ: | Sacro-iliac joint. |
| VO ₂ max: | Maximum Oxygen consumption. |

LIST OF PUBLICATIONS FROM THE WORK IN THIS THESIS

Published paper

Wilson F, Gissane C, Gormley J, Simms CK (2010) A 12 month prospective cohort study of injury in international rowers. *British Journal of Sports Medicine*, 44, 207-214.

Published abstracts

Wilson F, Gormley J, Simms CK (2006) A study to measure frontal plane angular changes in the lumbar spine of elite rowers. *Journal of Biomechanics*, 39, S545.

Wilson F, Gormley J, Simms CK (2005) A 12 month prospective study of injury and associated risk factors in rowing. *British Journal of Sports Medicine*, 39, 373-408.

Accepted abstracts

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Rowing is a sport which continues to grow in popularity throughout the world. It has been one of Ireland's most successful international sports in the last twenty years, boasting four World Champion rowers, a world record holder and numerous international medal holders.

1.1.1 The history of rowing.

Rowing is an ancient sport. Boats which were propelled by long oars can be seen in frescoes from the 5th dynasty of the Pharaohs of Egypt in 2500BC and ancient cultures where rowing was important, particularly during war, were the Greeks, Romans, Venetians and Vikings (Secher and Volianitis, 2007). The design of traditional Viking longboats contributed to their successful invasion of Europe, including Ireland. Dublin was a flourishing Viking port and it is likely that rowing was seen on the river Liffey, although in boats very different to those seen today. However, the form of such boats has evolved into what are now modern racing boats crewed by one, two, four or eight rowers.

The first modern international race took place between England and the USA in 1825 and the first Oxford and Cambridge boat race took place in 1829. Perhaps the best known rowing regatta, the Royal Henley Regatta was established in 1839 and has been held annually since that time (Secher and Volianitis, 2007).

1.1.2 Racing boat design.

The original racing boats were wooden and the early oars were also wooden with a spoon shaped oar or 'blade'. This design of boat was used until the late 20th century when carbon fibre boats and oars were introduced. This equipment was considerably lighter and stiffer meaning increased speed and efficiency. Racing boats may be divided into 'sculling' boats or 'sweep oar' boats. In a sculling boat, each rower has two oars and moves directly forwards and backwards on a sliding seat. In a sweep oar boat, the rower has only one oar and must rotate around their rigger as they move up on the sliding seat. The different parts of the boat are illustrated below on a single scull (Figure 1.0).

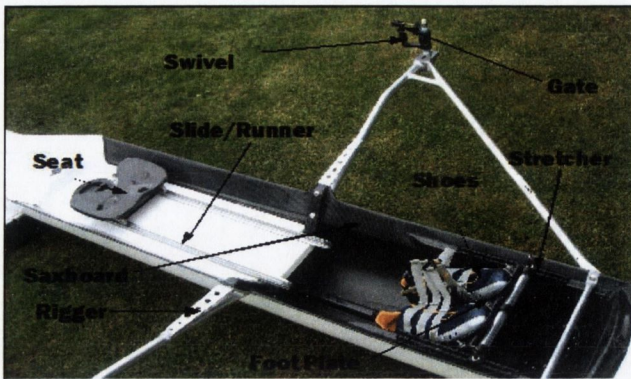


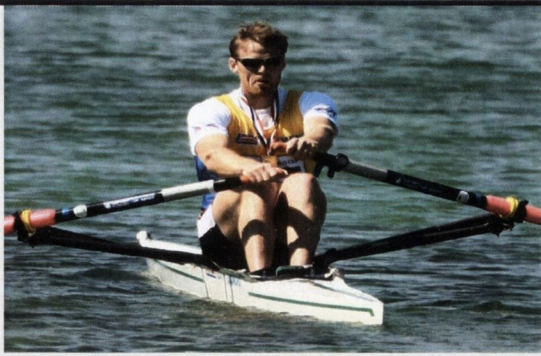
Figure 1.0: The component parts of a modern racing single scull.

(www.undeb.bangor.ac.uk.)

There are a number of classes of racing boats. The boats may be coxed or coxless. The job of the Coxswain or 'Cox' is to sit at the end or stern of the boat and to steer the boat using wires connected to a rudder. The smallest boat is the single scull (1x) with one rower who has 2 oars. The other sculling boats are the double scull or 2x, (2 rowers with 2 oars each) and quadruple scull or 4x, (4 rowers with 2 oars each), (Figure 1.1).

The smallest sweep oar boat is the coxless pair (2-) which consists of 2 rowers with one oar each. The other sweep oar boats are the coxless 4 (4-) which has 4 rowers with one oar each or the 8 (8+) which is the largest sweep boat and has 8 athletes with one oar each. The 8 is always a coxed boat but the four and the pair may be coxed (-) or coxless (+), (see Figure 1.1).

If the boat is coxless, it is steered by one of the rowers who has the rudder wire attached to the top of their shoe in the boat and who moves it side to side to move the rudder.



Single Scull (1x)

(www.olympics.org.uk)



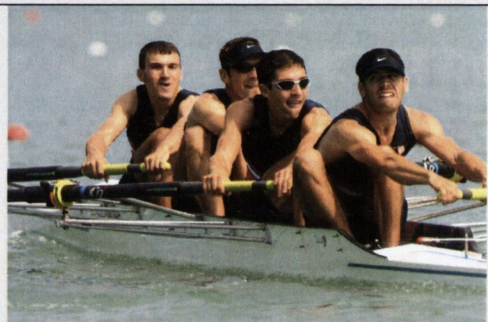
Coxless Pair (2-)

(www.abc.net.au)



Double scull (2x)

(www.olympics.org.uk)



Coxless four (4-)

(www.sherifu3.wordpress.com)



Quadruple scull (4x)

(www.olympics.org.uk)



Eight (8+)

(www.olympics.babyhook.com)

Figure 1.1: Classes of racing boats.

1.1.3 Oar design.

The original oars were little more than a long piece of wood with a flattened surface at the end but the early 20th century saw the introduction of the ‘Macon’ oar or ‘blade’ which had a much more definable spoon shape at the end of the wooden shaft. In 1977 the Dreissigacker brothers manufactured carbon fibre oars and later, a composite oar which are now used throughout the rowing population (Secher and Volianitis, 2007). Further changes have seen an increase in the size of the end of the oar (spoon) to a cleaver or hatchet shaped blade which allows greater purchase when the blade enters the water (Figure 1.2).

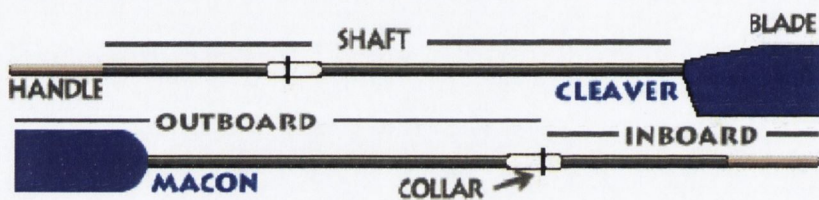


Figure 1.2: The design of oars or ‘blades’.

(www.bgsbc.co.uk)

1.1.4 Rowing ergometers.

Rowing ergometers are widely used by rowers throughout the world, both for training, testing and team selection. Rowing is weather dependent and high winds will often mean that athletes will be unable to train on the water, thus the ergometer is a useful training tool. Unless a rower is a single sculler, objective measurement of an athlete’s ability on the water is difficult as racing times will be dependent on other athletes’ performance. Thus the rowing ergometer presents an objective measure of the athlete’s performance and for this reason is usually one of the parameters used in selection of rowing teams. Furthermore, success on the rowing ergometer correlates well with success on the water in elite rowers. Mikulic et al (2009b) examined the 2000m ergometer times of 638 elite rowers and found that they were positively correlated with final rankings at the World Rowing Championships. The highest correlations were seen in male, lightweight single scullers ($r = 0.78$; $P=0.005$).

The most popular ergometer is the ‘Concept 2’ which has widespread use throughout the world both by rowers and non-rowers (Figure 1.3).



Figure 1.3: The Concept 2 rowing ergometer.

(www.concept2.com)

1.1.5 Racing.

The major international rowing events are the World Rowing Championships which are held annually and the Olympic Games which are held 4 yearly. The international governing rowing body which oversees these events is the Federation Internationale des Societes d’Aviron (FISA). Rowing races or ‘regattas’ are held over a 2000 metre rowing course and are usually held between May and late September and constitute the summer racing season. No formal international races take place out of this season although ‘head races’ take place between autumn and spring to introduce a break from training. The time it takes for an international rower to race over 2000m can vary from around 5½ minutes for the fastest boat (men’s 8+) to around 8 minutes for the slowest boat (women’s lightweight single scull).

1.1.6 Racing categories.

Men and women race separately and may race at junior level (under 18), under 23 (age 23 and under) or senior (any age over 18). There are two weight categories in rowing; lightweight and heavyweight. Lightweight women must have an average crew weight of 57kg with no athlete weighing more than 59kg. The international events which are available for lightweight women are the single and double scull and the coxless four. Lightweight men must have an average crew weight of 70kg with no athlete over 72.5kg. The international events available to lightweight men are the single, double and quadruple scull and the lightweight, coxless four and eight.

1.1.7 Rowing training.

Rowing is a sport where high volumes of training are observed, even at a very amateur level. Winter training (October to April) traditionally involves a combination of land and water training. Land training includes rowing ergometer work, weight training and other cross training which is aimed at increasing endurance such as running or cycling. The volume of time spent in the boat (water work) increases during the summer months. The aim of training in rowing is to train the aerobic and anaerobic systems appropriately. It may be divided into work which aims to improve oxygen utilisation with long distance training (on the water, ergometer or cross training such as running) or work to improve O₂ transport with interval training (Nilsen, 2007). Rowing training is traditionally divided into distinctive periods of time (periodisation) with specific objectives for each time period. Nilsen et al (2007) describe the 3 periods as the preparation period (6 months), the competition period (5 months) and the transition period (1 month). Nilsen et al (2007) suggest that the programme from October to August will require 650 hours of training with 4000 km covered on the water although an international elite rower will use 1500 hours of training per year and cover 7000-9000 km.

1.1.8 The inspiration for this study.

The ideas which generated this study came from my personal experience of rowing at an elite level. My rowing career was curtailed, just as I had achieved international selection, by a severe lumbar disc injury. I then worked with elite rowers for many years, first as physiotherapist to the South African Rowing Squad and then as Chief Physiotherapist to the Irish Amateur Rowing Union. The most common injury that I treated in the rowers that I worked with was located in the lumbar spine. It seemed that most of the Irish International Rowing Team sustained this injury at some time in their careers. Liaison with other clinicians involved with treating this injury, confirmed that the aetiology was poorly understood as there had been limited research in the area, particularly beyond analysis of ergometer training. As a clinician, the key to management of an injury is a clear understanding of aetiology and risk factors. The first stage of this study was to review literature relating to this injury, to identify where further study was required; this follows in section 1.2. The following stages were to produce studies which would increase the body of knowledge with the ultimate hope that it may improve understanding of lumbar spine injury in rowers.

1.2 LITERATURE REVIEW

The aim of the following review of literature is to examine studies which have investigated physiology, anthropometrics, performance assessment and biomechanics of the sport, to help to understand the demands of the sport on the rower. The injuries associated with rowing will be reviewed with critical reference to best practice in sports injury surveillance. The prevalence of the most common injury will be reviewed in the normal population with reference to risk factors and kinematics, to help put its incidence in rowers into context. Literature which has investigated such injury in rowers will be reviewed to analyse the specific biomechanics associated with the most common injury and to review kinematic analysis of this injury in the specific rowing population.

1.2.1 The physiology of rowing.

Rowing is fairly unique, in that it is a sport in which almost every muscle group takes part, which is in contrast to sports such as cycling or running. Physiological variables change dramatically during 'all out' rowing because of the workload required in all the limbs as well as the trunk. Also, in most sports, force is applied alternately on the left and right limbs but in rowing, the legs and arms work simultaneously requiring tremendous, sustained effort and load on the participants' physiology (Secher, 1993). To understand the physiological requirements of rowing, a standard 2000m race may be divided into 3 phases; the start, the middle and the sprint phase. The first phase is started at a high stroke rate (the number of times the oar enters the water in a minute) in an effort to get the boat moving from a standing start and the speed of the boat will be higher than in the middle phase of the race. The speed and effort of this phase means that the process is anaerobic and results in rapid accumulation of blood lactate. The middle phase of the race sees the stroke rate lower and the athlete 'settle in' to a sustainable pace for 4-6 minutes. Metabolism in this phase is aerobic. The final phase of the race will see the stroke rate rise again gradually until the rowers are pushing themselves at absolute capacity in a sprint to the finish line. As this phase is again anaerobic, it is associated with blood lactate accumulation and resultant muscle pain for the athlete (Nilsen, 2007).

Thus, aerobic metabolism constitutes 75-80% of the energy used in a rowing race and successful rowers demonstrate very large values for VO_{2max} for this reason. VO_{2max} is defined as 'the maximum rate at which an individual can take up and utilise oxygen while

breathing at sea level' (Eston and Reilly, 2001). The skeletal muscles of rowers are characterised by approximately 70-75% slow twitch muscle fibres (Secher, 1993). Mean VO_2max values of 6.5 (0.4) litres/minute has been reported in international rowers (Fiskerstrand and Seiler, 2004).

With the hyperventilation associated with rowing, the PaCO_2 decreases, resulting in reduced cerebral blood flow. The associated hypoxaemia causes a reduction in cerebral flow which means that cerebral oxygenation reduces by around 10% which is a magnitude which is frequently associated with fainting (Madsen and Secher, 1999).

1.2.2. Anthropometrics of a rower.

General observation would reveal that successful rowers are tall individuals with long limbs and a relatively short trunk. The elite male rower is 'around 195cm and weighs approximately 95kg while the female counterpart is 182cm tall and weighs 80kg' (Secher, 1993) with '70-85% slow twitch muscle fibres' (Steinacker and Secher, 1993). Volianitis and Secher (2009) state that rowers are 'around 30% taller than the average human'. A number of studies have confirmed this observation. Kerr et al., (2007) measured 38 anthropometric dimensions in rowers competing at the 2000 Olympic Games. The authors found that, when compared to age matched, non rowing controls, the rowers were proportionally heavier with greater proportional chest, waist and thigh dimensions but a smaller hip girth. They also found that the most successful individuals were the tallest and heaviest. In male lightweight rowers, the most successful individuals had greater thigh length (i.e., longer legs) than those who were less successful. In the female rowers the most successful athletes possessed the lowest percentage body fat, measured by skinfold thickness. Derose et al., (1989), Slater et al., (2005) and Mikulic (2008) found a short sitting height and longer limb characteristics in successful elite rowers. Slater et al also found a longer arm length to stature ratio when elite lightweight rowers were measured. It is perhaps not surprising that Slater et al., (2005) found that the most successful lightweight rowers were those who had a lower body fat and greater total muscle mass. Anthropometric characteristics are used as a criterion for selection of rowers by coaches from an early age. Kaloupsis et al., (2008) and Bourgois et al., (2000) confirmed that even at junior level (age 16-18), the most successful rowers were heavier and taller with greater relative limb length. When Kaloupsis et al., compared the anthropometric variables of the rowers to an age matched reference group of controls age 11-16 years, the rowers were heavier and taller with a lower body mass index. The understanding of the importance of

the anthropometric variables has been used in recent years for very successful talent identification programmes both in Great Britain and Australia.

1.2.3. Performance assessment in rowing.

Assessment of a rower's performance is important for crew selection and to monitor the effect of training. It takes place in the form of field tests (in the boat, on the water) or laboratory tests (in a laboratory, usually on a rowing ergometer).

Assessment on the water has always been the source of much controversy as objectivity is difficult in boats containing more than one person. Single scullers will simply be raced against each other over a set distance with the winner named as the best athlete. However, in crew boats, it is impossible to know which athletes are contributing most to the speed of the boat and the coach will sometimes make a decision based on instinct and knowledge of an athlete's ability to perform under great pressure. A system which is often used to try and introduce some fairness is known as 'seat racing', switching rowers according to a matrix (Secher and Volianitis, 2007). Rowers will race a number of races over a set distance in various pair combinations. Points are awarded for each race placing and a rank order of athletes may then be produced. The production of portable equipment to measure physiological parameters such as blood lactate and heart rate has meant that tests which were previously only done in a laboratory setting may now be done with the athlete in the boat. However, environmental conditions are constantly changing when the rower is on the water, making standardisation difficult and this means that the laboratory setting is still very popular for providing accurate physiological assessment.

Testing in the laboratory will usually take place on the rowing ergometer, the Concept 2 being the machine of choice for most international teams. An incremental exercise test or 'step test' is frequently used to obtain a physiological profile of the rower. This test requires the rower to perform a rowing session on the ergometer which varies between 5 and 8 steps. Each step requires the rower to row at a set work load and stroke rate for a set period of time (usually 3 minutes). The work load and stroke rate is increased incrementally for each step until, by the last step, the athlete is working to maximum capacity or exhaustion. The test finishes when the rower is unable to continue. Heart rate and expired air are measured continually throughout the test and blood is sampled at the end of each step to obtain a blood lactate profile. This test means that VO_{2max} , lactate

threshold and heart rate profile may be established for the rower. Other laboratory tests which are commonly used are the 2000 metre test and the 6000 metre test. The 2000m is the most common and is frequently used to aid crew selection. The tests described above measure aerobic capacity. Anaerobic capacity is not assessed as frequently in rowing, but if required, a 60 second flat out sprint is selected on the rowing ergometer. The rower's capacity is measured by the distance covered in metres on the ergometer in that time period.

1.2.4. The biomechanics of rowing.

The Rowing stroke.

The basic biomechanics of rowing can be divided into two phases; the drive phase (Figure 1.4) and the recovery phase (Figure 1.5). The drive phase is the part of the stroke when the blade is in the water and the recovery phase is when the blade is moving forward over the top of the water. Thus, the drive phase is when the workload is applied and the recovery is its namesake in that the rower recovers in preparation for the next stroke.



Figure 1.4: The drive phase.



Figure 1.5: The recovery phase (www.britishrowing.org).

The drive phase of the stroke starts when the blade enters the water at ‘the catch’ (Figure 1.6) and finishes when the blade is drawn out of the water at ‘the finish’ (Figure 1.7). At the catch, the ankles, knees and hips are fully flexed. The rower places the blade in the water and applies a pressure, i.e. pulls the oar towards their chest. At the same time, they push with their feet on the footstretcher, extending their knees as quickly as possible to push into the drive phase. The hips are extended simultaneously and the trunk leans back. The movement of the different body segments occurs smoothly in the skilled rower. At the finish, the ankles are plantarflexed, the knees are extended and the hips and lumbar spine

are still flexed but in relative extension compared to the catch position. Once the blades are drawn out of the water, the elbows are quickly extended and the oar handles are moved forwards over the rower's extended knees. The rower slowly flexes the knees, hips and lumbar spine and moves up the slides on the seat to the catch position.



Figure 1.6: The catch.

(www.worldrowing.com)



Figure 1.7: The finish

In sweep rowing, the rower rotates in the thoracic spine as he moves to the catch position which means that the lumbar spine is side flexed as well as flexed and that the arm nearest to the rigger is slightly flexed (Figure 1.8).

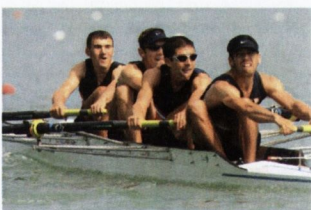


Figure 1.8: The catch position in sweep rowing *(www.sherifu3.wordpress.com).*

When the blade enters the water at the catch, it is perpendicular to the water and is drawn through the water in this position. When it is withdrawn from the water at the finish of the stroke it is done so by quickly turning it parallel to the water or 'feathering the blade' by the rower spinning the oar handle. It is kept in this parallel position until halfway through the recovery phase when the rower starts to feather or turn it again so that it enters the water perpendicular at the catch.

There are a number of different coaching approaches concerning application of pressure on the blade. However, generally in sculling, the blade is 'placed' in the water at the catch and accelerated through the stroke to the finish. In sweep rowing, the blade would be driven more forcefully at the catch, applying strong pressure much earlier in the stroke.

Forces acting on a boat.

When a rower applies force to an oar handle with their hands, and the foot stretcher with their feet, it is transferred to the blade which produces pressure on the water. This creates a reaction force on the blade which is what accelerates the boat through the water (Secher and Volianitis, 2007). The horizontal forces which oppose the motion of the boat consist of the hydrodynamic resistance of the hull together with the air drag of the hull and the rower. The propulsive force to overcome these forces is provided by the rower through the oar blades and is a result of a phased muscular activation by the rower (Baudouin and Hawkins, 2002). As the propulsive forces are intermittent, the boat experiences a time dependent motion, accelerating through the drive phase and decelerating through the recovery phase (Millward, 1987). Millward showed that the peak rowing force exerted on the blade was 308N to achieve a speed of 4.54ms^{-1} for an international lightweight crew at a stroke rate of 30 per minute. The average power needed was 354W to achieve this speed. However, Secher (1993) states that the peak force has been known to reach as high as 800-900N and Steinacker and Secher (1993) demonstrated that the force on the oars can reach between 1000 and 1500N at the start of a race. Soper and Hume (2004) report peak foot stretcher forces to vary between 299 and 600N. Martin and Bernfield (1980) showed that rowers who apply a steady force on the oar throughout the stroke cycle are able to produce the most power. The minimum velocity of the boat occurs approximately 27% into the drive phase and the maximum velocity is reached mid way through the drive phase (Martin and Bernfield, 1980).

Contribution of body segments.

The three body segments that contribute to the stroke are the arms, the legs and the trunk. The legs exert their maximum force at the catch and during the first half of the drive phase and produce almost half of the rowing power. The trunk produces 1/3 of the power and the arms produce the remainder (Secher, 1993). 'There are 3 forces acting on the rower which are at the foot, the seat and the hand. The rower generates the foot stretcher force directly by applying pressure at the catch and acts as the mechanical link between the foot stretcher force and oar handle force. The force developed in the hand on the oar handle is critical to the propulsive force developed at the blade and depends on the force on the foot stretcher and acceleration of the body' (Baudouin and Hawkins, 2002). Baudouin and Hawkins showed that rowing performance depends on the rower's ability to produce large foot stretcher forces. However, they noted that if the rower was able to produce a large pushing

force on the foot stretcher but their lower back could not support this force, the force transmission to the blade would be reduced because of back flexion. Thus the rower requires matching musculoskeletal strength across joints to maximise the impulse that is applied to the oar.

Balance of the rowing boat.

Rowing boats are unstable vessels and one of the keys to achieving good speed in a racing situation is for the boat to be stable. This is known as 'sitting the boat' and in simple terms, means that it does not topple to one side or the other and 'sits' in the middle of the hull on the water. This is a technique which is one of the most difficult to achieve in rowing and is probably proportional to experience. The boat has the vast majority of its movement in the rower's frontal plane i.e., it 'wobbles' from left to right (rather than forwards and backwards), as the rower sits in the boat on the water. Kerr (2010) provided a good explanation of the mechanics of this problem. He stated that rowing boats have a centre of gravity which is some distance above the centre of buoyancy of the boat. Due to its hull shape, no rowing boat is ever statically stable but can be held 'flat' by skimming the blades on the water and/or body inertia. Skimming the blades on the water will slow the boat down so rowers usually choose body inertia to instinctively 'sit' the boat. Kerr states that balance and 'flatness' are not the same thing; it is possible to have a balanced boat that is not flat and it is also possible to have a flat boat that is not truly balanced in that it is in static equilibrium. Rowers ultimately care about flatness. The faster the boat is moving, the more easily it may be balanced or sit flat. The evolution of racing boats has made them narrower and lighter and a racing sculling boat is only a few centimetres wider than the rower's hips but it means that the rower is sitting on a narrow unstable surface.

Nolte (2005) analysed the implications for a crew boat that is unbalanced. He noted that for a sweep boat that is only 1 degree out of balance, the rowers on one side of the boat carry the oars about 5 cm higher than the rowers on the other side in a boat which is rigged to within millimetre adjustments to allow accuracy. Also, as the rolling of the boat is transferred to the seats that the rowers are sitting on, the rowers shift their bodies through movements in their lower back to try and regain balance. Nolte stated that this can lead to extended loads in the lower back which may increase injury risk in this region. Nolte summarised the intrinsic factors which can influence the boat balance as: a change in hand height during the recovery; a small shift of the upper body; swaying of the legs during the

recovery; movements, however small, on the rudder. Balance drills form a very important part of technical training on the water for all rowers.

Comparison of rowing boat and ergometer biomechanics.

The difficult task of balancing a rowing boat has been outlined above and this is probably the most obvious difference between ergometer and on-water rowing. A boat is an unstable vessel on an unstable surface and an ergometer is a rigid structure on a stable surface. However, only a small number of studies have analysed the differences between ergometer and on-water kinematics.

Lamb (1989) filmed 30 international rowers on a rowing ergometer and then on the water while rowing in an 8. For the ergometer filming, the camera was placed at right angles to the plane of motion at a distance of 15m and the on-water filming session involved a mounted camera on a motor propelled boat that was kept parallel and at a distance of 20 m from the rowing 8. The rower's movement was analysed in the sagittal plane only in this study. Lamb found that most of the kinematic variables of all subjects were similar throughout the drive phase, particularly for the legs and trunk. Lamb also showed that the trunk and legs were the prime contributors to the drive phase of sweep rowing. There was a significant difference however in the upper and lower arm components of rowing at the beginning and end of the drive phase when the ergometer and boat data was compared. Lamb explained this by suggesting that the slippage of the oar in the water creates a situation in which the arms compensate for the non stationary fulcrum of the oar in the water whereas the catch position in ergometer rowing occurs around a fulcrum that is fixed and remains stationary. Thus, the leverage of pull on the oar is greater for ergometer rowing than for water rowing. The arm segments were also different at the end of the drive phase which might be explained by the need to feather the oar in boat rowing. The fact that measurements were in the sagittal plane only in this study will have introduced error in sweep rowing as trunk rotation takes place. Thus, two different movement patterns were assessed as there is no trunk rotation in ergometer rowing. Data may have been more accurate if sculling was assessed. Also, there may have been parallax errors in the on-water filming. However, considering the available technology at the time, this study provided some useful findings.

Kleshnev (2003) summarised a number of observations gleaned from a comparison of water (sculling) and ergometer rowing. He showed that the foot stretcher force develops much earlier on the ergometer as a result of higher inertia forces which the rower has to overcome to change direction of body mass movement and the handle force on the ergometer has a higher peak and develops later. Kleshnev (2005) showed that rowers have a 3-5% longer stroke on an ergometer because of an 8-10% longer leg drive. He also showed that the foot stretcher force on the water is 30% higher than that of the handle force, while on the ergometer, they are nearly equal. Difference in power production of the body segments are seen between the water and the ergometer. On the ergometer, the legs execute more work but in slower motion, while on the water, the legs work much faster at the catch when the force is not very high and thus execute less power.

Kleshnev (2003) summarised the body contributions on the ergometer as 37%: 41%: 22% (legs: trunk: arms) compared to the water as 45%: 37%: 18% (legs: trunk: arms), suggesting that rowers with fast leg drive produce more power on the water, while athletes with slower leg drive and stronger upper body have relatively higher ergometer scores.

There have been a very limited number of studies which looked at physiological differences between ergometer and water rowing. One small study (Gueval et al., 2006) demonstrated that the physiological parameters of heart rate and VO_2 max showed no difference in profile for individuals when the rowing types were compared. This indicates that despite the difference in kinematics, the ergometer is still a useful training and performance analysis tool for rowers. In summary, Kleshnev (2005) stated that there is a 60-80% similarity between ergometer and on water rowing.

1.2.5 Summary of section 1.1 and 1.2.

Rowing is a very old sport which has evolved in terms of technique, training and equipment, particularly in the latter half of the 20th century. Modern boats are light and streamlined with hydrodynamics which aim to optimise the forces generated by the rower. Modern oars aim to increase the force the rower is able to apply in the water by reducing slippage and giving best purchase. Rowers are tall, strong individuals with long limbs relative to trunk size. They have muscles which have a majority of slow twitch fibres, and physiology suited to success in endurance activity. The volume of training completed by rowers is high, particularly those competing at international level. Rowing training

involves a combination of land and water training which varies throughout the year. Land training has a particular emphasis on rowing ergometer training even though limited research highlights important differences in kinematics between water rowing and ergometer rowing. Despite this, performance assessment in rowing is difficult, particularly in crew rowing and the ergometer is used widely in team selection and for monitoring progress. For this reason, it remains a crucial part of the rower's training programme. The biomechanics of rowing are complex and many variables contribute to the speed of the boat. Unlike most sports, a number of body segments work simultaneously which make it unique in a number of ways. There are a number of specific points of loading on the rower's body where high forces are generated. Due to the cyclical movement pattern and high volume of training, these forces are repeated hundreds of times during a typical training session. It seems likely that the combination of forces acting on the rower, volumes of training or type of training place the rower at risk of injury. This will be discussed in the following sections.

1.3 Injury in rowers.

1.3.1 Sports injury surveillance.

To assess the quality of sports injury research, it is first necessary to quantify what constitutes best practice. There has been considerable interest in this topic in recent years, particularly as sport becomes more professional and many sporting injuries may now be defined as an occupational injury.

Thacker (2007) defines injury surveillance as 'the routine, on-going collection, analysis and dissemination of data to those responsible for preventing and controlling disease and injury'. Thacker further advocates that 'good injury surveillance provides: data needed to assess the status of the injury problem; early warning of injury problems to guide control measures; a quantitative basis to specify prevention objectives; information to design and plan prevention programmes; measures to evaluate interventions; a quantitative basis to plan research agenda and data archives to describe the natural history of an injury problem.' Despite well established injury and disease surveillance in public health, epidemiological research in sport is still relatively new and few countries have specific public policies to deal with such. Australia leads the world with policies such as the National Sports Safety Framework which was implemented in 1997 (Mitchell et al., 2008). Van Mechelen (1997a) outlined the sequence of events which represents best practice in

sports injury surveillance; this was adapted from traditional public health surveillance models (Figure 1.9).

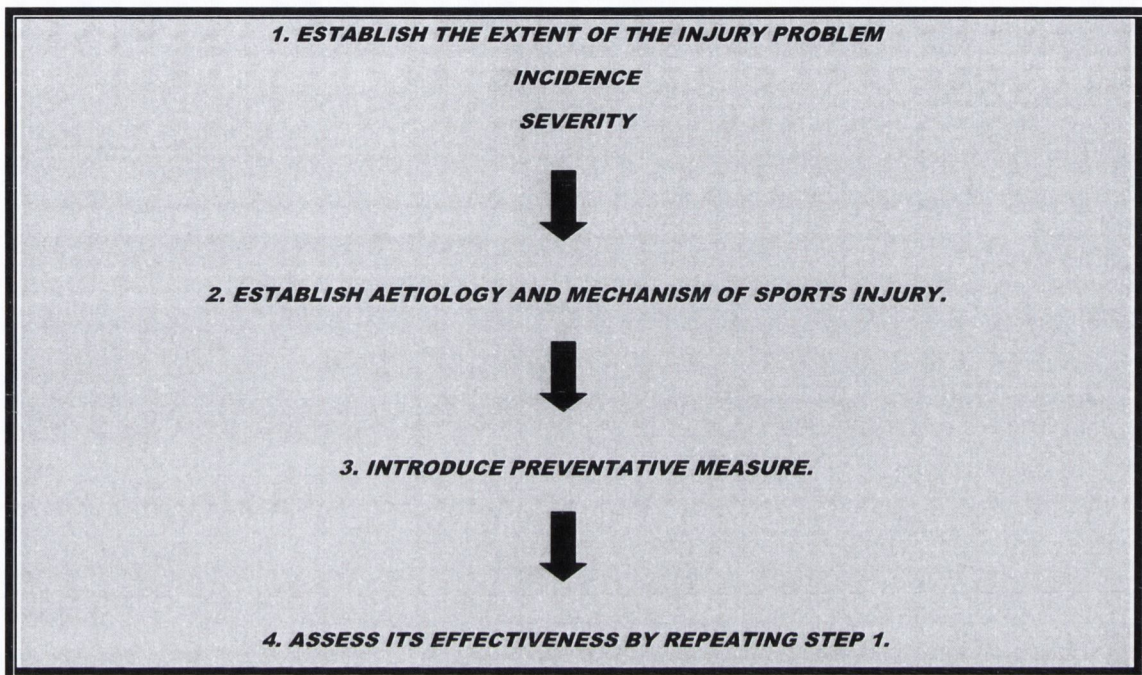


Figure 1.9: Van Mechelen's sports injury surveillance framework.

Van Mechelen (1997a) emphasised the importance of defining a clear research question before initiating the injury surveillance programme. This question is usually a case of 'how many, how often, how long, how serious'? To answer such questions, the injury surveillance system will need to assess the injury rate (taking exposure into account), injury prevalence (the proportion of subjects with an injury in the specified population at any one time) and the duration and severity of the injury in terms of times lost from activity or competition.

The design of the study will naturally depend on the research question and may be experimental or observational. The most common observational designs in sports injury surveillance are: cohort studies; case-control studies; cross-sectional studies; case series and case reports (Borchers and Best, 2010). To maximise validity and reliability in sports injury surveillance, Borchers and Best identified the most common sources of bias and confounding and random error.

The most common causes of bias are in selection bias in that the most motivated athletes are frequently the subjects most easily selected. Observation bias is also regularly seen in recall details of an injury; the athlete may forget or misreport important details of an injury which is particularly affected by the time period of recall. A common confounder in sports injury data is the presence of a recent previous injury which has a strong relationship with current injury risk and will alter the results if not accounted for. Random error is most frequently produced by limited sample size and, as in any research, is avoided by appropriate sample size calculation prior to the study. However, in sports injury epidemiology, the available sample size is frequently limited (for example, when assessing international athletes) which means that there is a limit to how much random error may be avoided.

While clinical trials are the most popular method to investigate the effect of an intervention, they are usually preceded by cohort studies which provide descriptive data on which the intervention is designed. Cohort studies may be prospective or retrospective in nature although prospective studies are better as retrospective studies are affected by observational bias and confounding. Clinical trials are always prospective in nature. Case control studies are efficient for studying rare outcomes but the retrospective nature can lead to increased bias. Descriptive studies are a subset of observational studies and are not as effective as cohort and case control studies in establishing causation between an exposure and outcome. A cross-sectional study design is frequently used in this instance to establish the point prevalence of an outcome and associations between exposures or variables. Case series and case reports are also descriptive studies which can describe outcomes and associated exposure or variables but cannot establish causation. Case studies and reports often initiate interest in an outcome which may be investigated further with a more robust study design (Borchers and Best, 2010).

Definition of injury.

The ultimate aim of sports injury surveillance is to produce a body of knowledge that allows a greater understanding of injuries. Comparison of studies requires standardised definitions of injury and this is an issue which has induced debate. Finch (1997) stated that 'standardised definitions are needed when different sports activities are to be compared or when data from a number of different sources about a given sport are to be collated'. Fuller (2010) recommends a set of criteria that should be considered when designing an effective

operational definition of injury. These are: 1) what conditions should be counted as an injury? 2) How will the severity of the injury be measured?

3) How will the injury be classified in terms of location and pathology? 4) What is the underlying cause of the injury? Fuller et al., (2006) produced a consensus statement on injury definitions and data collection procedures in studies of football injuries. This definition is given as:

'Any physical complaint sustained by a player that results from a football match or football training, irrespective of the need for medical attention or time loss from football activities. An injury that results in a player receiving medical attention is referred to as a 'medical attention' injury, and an injury that results in a player not being able to take full part in future football training or match play as a 'time loss' injury'

This definition has been widely quoted and accepted with minor alterations in a number of sports including rugby league (King et al., 2009a), rugby union (Fuller et al., 2007) and in multi sports events (Junge et al., 2008). Previous studies have used a narrow definition of injury which only included those that caused the player to miss a match, because of its inferred reliability, but this caused many minor injuries to be missed (Hodgson et al., 2007). For some studies it is also necessary to define if the injury is a 'new injury' or 'recurrent' injury.

Severity of injury.

Fuller et al., (2006) defined injury severity as:

'The number of days that have elapsed from the date of injury to the date of the player's return to full participation in team training and availability for match selection.'

The day on which the injury occurs is named as day zero and the days after are counted. The more severe the injury, the more time is lost from training or competing and severity is recorded in time loss. Time loss is one of the most popular methods of recording severity. However, severity may also be measured by the nature of the injury and/or the type of medical attention that is required and this is one of the areas that there are presently a number of approaches and some consensus is lacking.

Orchard et al., (2007) argue that for team sports, match time loss is the only definition that can be 'reliably and accurately applied' and that no study using a broad definition has

demonstrated good reliability to date. However, rowing is a case where this injury definition would not be useful as rowers not only compete infrequently, but are likely to replace one type of cross training for another when they are limited by injury. Van Mechelen (1997b) suggests that the criteria that should be considered when judging severity of injury are: nature of the injury; duration and nature of treatment; sporting time lost; working time lost; permanent damage; monetary cost. It may be proposed that the most appropriate way to define severity is according to the research question and the type of sport being evaluated.

Match and training exposure.

To allow comparison of different studies, exposure data is required as this allows an injury rate to be constructed. This is expressed in a standard way as 'injury incidence per 1000 hours' of exposure to the sport (King et al., 2009a). It can be further analysed as incidence per 1000 *match* hours or *training* hours. Fuller et al., (2006) stated that match and training exposure should be combined with a prospective cohort study to 'enable relations between the incidence of injury and risk factors in the study population to be explored'. This clear definition of injury rate according to exposure is important to compare injury profiles across sports.

Injury Classification

Injury should be classified by location, type, body side, mechanism or causation of injury (traumatic or overuse) and whether the injury was a recurrence. Fuller et al., (2006) define a traumatic injury to be an injury which results from a single identifiable event and an overuse injury to be caused by repeated microtrauma without a single identifiable event responsible for the injury.

There are a number of different classification systems for injuries but one of the most popular is probably the Orchard Sports Injury Classification System (OSICS) which was developed in 1992 and has been regularly modified so that OSICS version 10 is the most up to date. The OSICS – 10 allows classification of injuries into an easily tabulated version and records location, type, body side and injury mechanism in standard codes (Fuller, 2010).

Baseline information

Fuller et al., (2006) and King et al., (2009a) both advise inclusion of baseline information for each study participant. Both recommend information such as the player's age, gender, height and body mass. Further information, such as playing/ competing experience and playing position, help to define the study population.

Reporting of data.

Fuller et al., (2006) summarised the points that are important in reporting data. The cohort should be defined by reporting numbers of participants, age range and gender and the duration of the study should be identified. The definition of injury should be provided. The number of injuries occurring during matches and training should be reported separately with the match and training exposures so that the injuries can be reported separately. The incidence of injuries should be reported per 1000 player hours. While the severity of injury may be reported by both time loss and medical attention, both should be reported if possible to allow comparison with other studies. Injuries should be classified by a standard classification system. The inclusion of other results will depend on the specific purpose of the study but may include training details to allow more in depth information to be gleaned regarding cause of injury.

Risk factors.

It is pertinent at this juncture to discuss the concept of 'risk factors' as it is a phrase that will arise throughout this thesis. A risk factor is defined by the Oxford Medical Dictionary (1997) as:

'An attribute, such as a habit (e.g. cigarette smoking) or exposure to some environmental hazard, that leads the individual concerned to have a greater likelihood of developing an illness. The relationship is one of probability and as such can be distinguished from a causal agent'

The term risk factor is used throughout medical literature and will be referred to both in sport injury surveillance and low back pain epidemiology in the following text. However a number of criteria have been established which must be present to class a component as a risk factor. Hill (1965) outlined a set of epidemiological criteria which are necessary to establish causation and therefore term something a 'risk factor'. These criteria comprise the following: Temporality; Strength; Dose-response relationship; Consistency; Plausibility; Coherence; Analogy; Experiment; Specificity.

Hill's criteria are explained by Krosshaug and Verhagen (2010) as the following:

1. *Temporality*. Exposure to a causal factor always precedes the outcome. This is the most essential criterion to establish a causal relationship.
2. *Strength*. The stronger the relationship between the risk factor and the injury risk, the less likely that it is that the relationship is due to an extraneous variable.
3. *Dose-response relationship*. The stronger the presence of a specific factor, the higher the risk of injury. The incidence of injury should also decline when exposure to the factor is reduced or eliminated.
4. *Consistency*. An association should be consistent when results are replicated in studies in different settings using different methods.
5. *Plausibility*. There must be a rational basis for positing an association between a risk factor and an injury.
6. *Coherence*. A causal association should be compatible with existing theory and knowledge.
7. *Analogy*. An accepted phenomenon in one area can be applied to another.
8. *Experiment*. The injury can be prevented or minimised in severity by an experimental regimen.
9. *Specificity*. A single alleged risk factor produces a specific injury, i.e. the effect has only one cause.

Thus, to describe something as a risk factor requires fulfilment of a robust set of criteria. However, the term is continually used in a less appropriate way, throughout the following literature review to describe an *association* of a variable with an injury onset which is obviously incorrect. For the purposes of this thesis, when the term risk factor is used in the literature, it will not be analysed further but it must be considered in the context of Hill's criteria. Furthermore, it should be noted that risk factors are very different from *injury mechanisms*. Risk factors occur distant from the injury outcome whereas injury mechanisms occur proximal to the outcome and only mark the onset of the injury but not be considered as the only or exclusive cause (Meeuwisse and Hagel, 2010).

1.3.2. Studies of injury profile in rowing.

A search was carried out using the terms: *rowing; rowing injury; rowers; rower's injury; injury + rowing; injury+ rowers*. The search engines of Embase, Pubmed, Cinahl, Science Direct, Google Scholar, AMED and Web of Science were investigated. The final search was carried out in December 2009. Studies were limited to those which were in English and involved humans. No date limit was set. Ninety one studies were accessed initially. Of these, the following were excluded: Review papers (16); Studies of rib stress fractures only (9); Rowing kinematics and biomechanics studies (14); Physiology studies (18); Studies which were not specific to rowing such as the use of rowing as rehabilitation in spinal cord injury (11); Single case studies (4); Nutrition studies (2); Surfboat rowing studies (1); Studies of general illness in rowers (2). This left a small number of studies indicating a paucity of studies in the area. Of these, 9 were genuine studies of injury in rowing and 5 were studies of lumbar spine injury in rowing. Most studies consisted of a retrospective questionnaire of injury rate or a retrospective review of athlete attendances at a specific sports injury clinic. Of the questionnaires, all were carried out on elite rowers, most of whom were international standard at a specific training camp or international competition. Other studies analysed a specific injury in rowing and will be discussed later in this section.

General injury surveillance in rowing.

Budgett and Fuller (1989) surveyed 81 rowers of whom 85% responded. All rowers were aspirants for the 1987 British Rowing Team and completed a retrospective questionnaire at the end of the 1987 season. The questionnaire investigated the incidence, nature, severity and mechanism of injuries, time lost from training and type of treatment received. Seventy two percent of the cohort reported at least one injury in the previous twelve months and 6% reported two injuries. The most common injury was to the lumbar spine accounting for more than half of reported injuries (30 reported cases), most occurred during weight or circuit training, significantly more than during running or rowing. The next most common injury was to the knee, all of which occurred during weight training or running. The average number of days lost per athlete through injury was 12.8.

The retrospective design of this study is likely to have introduced recall bias. All injuries were self reported which meant that no specific diagnoses or injured structures were described and injury could only be reported by site. The authors reported that most back injuries occurred during weight training but no further information regarding whether this

was an acute event was given. It therefore cannot be concluded that weight training is the cause of back injuries as the injury onset may have been preceded by a variety of other training types. It would have been better to report the nature of the injury onset i.e. acute or overuse, as outlined above in best practice. No training and racing data was collected so the authors were unable to report the injury incidence

/1000 hours although the authors estimated the injury incidence at 1/1000 hours by presuming that all athletes were completing the same training schedule as outlined by the international rowing body. However, there is no data to confirm that the training did take this long and is likely to differ for each athlete. Despite this, as a descriptive study, it highlights the high incidence of lumbar spine injury in particular in this population.

A retrospective survey of three years of medical records of 180 college rowers by Boland and Hosea (1991) was conducted with the aim of examining injury site and diagnosis only. The findings concurred with Budgett and Fuller's, showing that the most common injuries were to the knee (25% of injuries) and lumbar spine (19%) of injuries. However, Boland and Hosea's study did not provide any training or racing data and thus could not provide injury incidence/1000 hours; furthermore, no mechanism or severity of injury was reported. The most commonly reported injury to the lumbar spine was 'mechanical back pain' (74% of lumbar spine injuries). Herniated lumbar disc represented 13% of lumbar spine injuries and Spondylolysis also represented 13% of reported injuries. Although this study was simple in that it reported injury site and diagnosis only, the data was collected from medical records and thus the injury site is likely to be more accurate than self-report data.

More recently, Smoljanovic et al., (2009) surveyed junior international rowers at the 2007 Junior World Rowing Championships. The rowers completed a retrospective questionnaire which examined injury and training details over the previous 12 months. Injuries were classified by site and divided into traumatic and overuse and were classified by the loss of training time (if present) into minor, moderate and major injury types. A total of 398 rowers completed the questionnaire and of these, 217 reported an injury which produced an injury incidence of 0.99 per rower. The authors reported the injury incidence as 2.1 per 1000 training sessions. The most commonly reported injury mechanism was overuse and the most commonly reported injury site was the lumbar spine (127 injuries) followed by the knee (74 injuries) and wrist (45 injuries). Most injuries did not report any time lost from rowing although 6 of the lumbar spine injuries required more than 1 month

absence from rowing. Traumatic injuries were reported by naming the activity during onset. Of these, most were sustained while cross training (9.7%) followed by 'on the water' (8.9%), while just 1.8% of injuries were sustained while rowing on the ergometer. Of the 7 injuries that were sustained while using an ergometer, 5 were to the lumbar spine and 2 were to the shoulder.

The authors found no significant association between the average length of training sessions on the ergometer and low back injury. When traumatic injuries in the gym were analysed, the most frequently injured area was the lumbar spine. Five stress fractures were reported in this cohort, all of which were reported in females. Those rowers who averaged more than 7 training sessions per week had significantly more total injuries and more overuse lumbar spine injuries, compared with those who completed fewer training sessions per week. An increase in on-water training was significantly associated with higher frequency of overall injury and low back injury. Those rowers who reported stretching for at least 10 minutes per day were associated with less traumatic injuries.

This study is probably the most comprehensive study of rowing injuries to date as it attempted to collect training data and injury mechanisms to establish factors which may help predict injury. However, as the study was a retrospective questionnaire, recall bias is a likely source of error. It is unlikely that any subject accurately reported training hours for the previous 12 months and, without collecting exact data, there may have been either an underestimation or overestimation of time spent stretching, particularly as this was likely to vary daily. All injuries were self reported which may have introduced error in naming of the injury site; a hip or knee injury may have been a referral from the lumbar spine. Best practice requires that injury incidence is reported per 1000 hours. However, the authors in the study reported the incidence per 1000 training sessions which means that comparison with other studies is not possible; it is unlikely that a retrospective survey could produce good accuracy in reporting of hours of training over a previous 12 month period. Despite the limitations of this study, it again highlights the high incidence of lumbar spine injury, in agreement with Budgett and Fuller (1989). Although attempts were made to suggest factors which may have contributed to this injury, limitations in methodology prevented any clear conclusions.

A common critique of the studies which have been reviewed thus far is that all injuries were self reported by the athletes, who were required to remember details of the injury

which may have happened up to 12 months previously. There are a number of published studies which review injuries which were all diagnosed by a chartered physiotherapist or doctor and outline injury mechanism and onset details which were collected around the time of the injury.

Devereaux and Lachman (1983) conducted a prospective study over a 2 year period. They analysed all injuries attending a sports injury clinic and recorded injury nature and mechanism. All athletes were examined and treated by a chartered physiotherapist. Of 1186 injuries recorded over a 2 year period, five sports were associated with over 70% of the injuries; these were soccer, rugby, running, squash and rowing. Rowing constituted 8.3% of all recorded injuries compared to the most common which was soccer which constituted 19.4% of all injuries. The most common injuries in rowers were 'lumbar strain' and 'wrist tendinitis' which represented 2.4% and 2% respectively of all reported injuries. They further noted that lumbar strain caused 28% of the injuries observed in rowers.

While this study did not present information regarding injury mechanisms and possible associated factors in rowers, it did present rowing injuries in the context of general sporting injury, suggesting that the risk of sustaining an injury in rowing was around half that reported in soccer. Also, the findings concur with those studies reviewed above which note that lumbar spine injury is the most commonly reported injury in rowers.

Parkkari et al., (2004) carried out a large scale study which analysed active living and injury risk, the purpose of which was to examine the risk in various commuting and lifestyle activities as well as recreational and competitive sports. A cohort of 3363 Finnish adults recorded all their physical activities that lasted 15 minutes or more, registering all acute and overuse injuries that occurred during these activities. From this methodology, it was possible to establish an injury incidence of 1.5/1000 hours in rowing which is very low when compared to the injury rate in squash which was 18.3/1000 hours. This study presents very limited data in the analysis of rowing injury other than incidence and severity (very low for rowing in this case). However, the method adheres to standard injury and severity definitions allowing comparison of injury rates across sports. Also, as the method of collecting injury and exposure data was prospective and was the same for all the study population, it is likely to be one of the only studies that reliably reports an injury incidence / 1000 hours for rowing.

Reid et al., (1989) carried out a retrospective survey on the medical records of the Sports Medicine Unit at the Australian Institute of Sport. Four years of records of female rowers were analysed, which constituted 40 athletes, of whom, 25 reported an injury over that time period. Sixty new injuries were seen, of which 15 were to the spine which was the most commonly reported injury. The next most common injury was to the chest wall (13 injuries) followed by the forearm (12 injuries). Only 2 of the lumbar spine injuries had a specific diagnosis which was a disc injury. Most of the lumbar spine injuries presented in months when a lot of weight training was done and the authors suggested that most of the back problems were not related to rowing itself but to weight training programmes. The authors also noted that no back injuries occurred in the last year of analysis and suggested that this may be related to the fact that the weight training programme changed in this year from intense heavy weights to more of an 'endurance type' programme as well as the introduction of daily strengthening exercises for the abdominal and lumbar supporting muscles.

The fact that all these injuries were diagnosed by a physiotherapist or doctor means that this study presents an accurate picture of injury type for the regions. However, as no specific training and racing details were collected over the 4 year period, the authors can only speculate which training mode caused the injury. A chronic lumbar spine injury may have suffered an acute exacerbation during weight training rather than be caused by it, which suggests that much more detail is required in preceding training and racing exposure to see which training mode presented the greatest injury risk. As discussed in section 1.3.1, activity at time of injury should be regarded as injury mechanism and does not indicate causation. Because the methodology of this study was a retrospective survey, no injury incidence / 1000 hours was established.

The Australian Institute of Sport was also the setting for a review of rowing injuries presenting over the previous 12 month period (Coburn and Wajswelner, 1993). It was established that 65% of injuries were from 'rowing itself' and 28% occurred 'in the weights room'. The lower back made up 45% of all documented injuries and the authors reported that weight training was the cause of 40% of the lower back injuries. Again, the method of this study means that no training or racing data was collected and that cause of injury is speculation. Nature of activity during onset of injury should not be cited as the cause of the injury for the reasons discussed in section 1.3.1.

The final analysis from the Australian Institute of Sport was published in 1997 by Hickey et al., (1997) who examined (retrospectively) all injuries in elite rowers over the previous 10 year period. Injuries were categorized according to time, location, cause and whether acute or chronic. They found that the mean injury incidence for females was 1.58 injuries/year and for males was 0.85 injuries/year. Chronic injuries made up 72.1% of the female injuries and 69.8% of the male injuries. The most common site of injury in the males was to the lumbar spine (25%), the forearm (15.5%) and the knee (12.9%). In females, the chest was the most commonly injured region (22.6%) followed by the lumbar spine (15.2%) and forearm (14.7%). Again, as no training or competition exposure time was available, no injury incidence /1000 hours was noted and as it was not possible to establish time loss from the medical notes, injury severity was not established, presenting a number of considerable limitations in this study.

Edgar (1993) reported rowing injuries presenting for treatment in the 4 weeks prior to, and during the 1992 Junior World Rowing Championships. As in all other studies, the most common injury was to the lumbar spine which made up 30% of all injuries reported by a total of 44 rowers. No details were given of injury mechanism or training details. This study was purely descriptive of injury type and represents a very small time period of the rower's training and racing year. However, it confirms again that lumbar spine injury is the most commonly reported injury for rowers.

Lumbar spine injury in rowing.

All of the studies reviewed so far have highlighted that the most commonly reported injury in rowing is to the lumbar spine. For this reason, other studies have focussed on this injury in an effort to produce a clearer profile of its aetiology.

Howell (1984) asked a cohort of 17 elite, lightweight female rowers to complete a questionnaire detailing present musculoskeletal symptoms, in particular the presence of low back pain, and further questions regarding the 'extent' of flexibility exercises carried out by each rower. The questionnaire was followed up by measurements of flexibility of the lumbar spine and related soft tissue and strength of the trunk musculature. Results showed that 82% of the rowers reported 'occasional or chronic low back pain or discomfort' However, this definition of injury lacks clarity. Also, only two of the rowers reported lumbar spine symptoms at the time of testing. As the authors did not report the time period during which the rowers should report these 'occasional symptoms' this

information adds little to the body of knowledge regarding specific rowing related injury. A clearer picture may have been ascertained if one of the standard injury definitions (see section 1.3.1) had been used. The authors reported that flexibility tests showed that 75% of the sample had 'hyperflexion' of the lumbar spine, although the sit and reach test was used to assess hyperflexion. The sit and reach test clearly measures hamstring length and larger movement may be obtained with greater hip and thoracic spine flexion, making it a very poor measure of lumbar flexion. As rowers sit in a 'long-sitting' position in the boat for long periods of time, it would be expected that rowers would achieve above normal results for this test. This study had many limitations, most notably, no specific injury definition, which meant that even rowers who reported 'tightness in the lower back after workouts' were classified as injured and thus the results must be interpreted with caution.

Bahr et al., (2004) aimed to compare the prevalence of low back pain in endurance athletes in a number of different sports which were rowing (199 subjects), cross country skiing (257 subjects) and orienteering (278 subjects). This group were compared with non athletic controls (197 subjects). A 12 month retrospective survey was completed by all participants which asked about the presence, type, site, severity (days of training or competition missed) and behaviour of low back pain. Fifty five percent of the rowers reported low back pain in the previous 12 months which compared with 63% in skiing, 49.8% in orienteering and 47.5% in the control group. Of note, the rowers reported the most missed training sessions because of injury and the greatest number of injuries requiring hospitalisation compared to the other groups. Although this study is retrospective with associated recall bias, it is useful in that it not only presents low back injury in rowing in context with other sports, but also with an age matched control group.

A number of surveys carried out on a large cohort of intercollegiate rowers are limited in some aspects of their methodology but make some useful conclusions. Teitz et al., (2002) surveyed 1632 former intercollegiate rowers investigating training methods and back pain before and during college rowing. A standard definition of injury was given. Thirty two percent of respondents reported back pain which developed during college rowing. Factors which were significantly associated with the development of back pain included age at the time of the survey; history of rowing before age 16; use of a hatchet oar; training with free weights, weight machines and ergometers; and ergometer training sessions lasting longer than 30 minutes. Of interest, the number of athletes who had back pain during college rowing increased significantly over the 20 years covered by the survey, from 18.8% to

those who were 41-45 years old at the time of the survey (who had probably started rowing up to 27 years previously) to 45.1% in those who were 20-30 years old (who would have started rowing more recently). While it may be that this is because of limited recall in the older cohort, it could also be a reflection of the great changes in training volume and equipment between 1980 and 2000 and merits further analysis. This is supported by the fact that athletes who trained within the last 10 years of the survey used a greater number of different training techniques which was significantly associated with higher injury rate.

The most commonly reported time of year to develop back pain was the winter months (38.7% of cases) compared to spring (32.7% of cases), autumn (24.5% of cases) and summer (3.7% of cases). A number of respondents reported that onset of back pain was associated with a specific event; outdoor rowing was the most common at 72.4% of cases followed by weight lifting (50%) and ergometer training (29.1%). A regression analysis showed that when training types were assessed, the only significant predictors of back pain for men were ergometer sessions which lasted longer than 30 minutes. In females, height was also significantly associated with back pain onset.

The time analysed by this survey is probably its greatest limitation and data recalled from a 20 year period is unlikely to be completely accurate. Also, the response rate of this survey was only 35% as 4680 athletes were originally surveyed. This may have introduced bias as respondents may be more likely to be back pain sufferers. Nevertheless, it highlights certain aspects of training which may be a likely factor in onset of low back pain in rowers. In particular, it is the only study to highlight an aspect of training (more than 30 minutes of ergometer training) which is a predictor for back pain. Previous studies have only linked activity at time of onset with injury and thus cannot be described as predictors for injury.

Teitz et al., (2003) followed up the initial study to examine if rowers who develop back pain in college are more likely than the general population to have back pain later in life. They found that rowers who developed back pain in college had more subsequent back pain than rowers who were asymptomatic in college (78.9% versus 37.9%), although the lifetime prevalence of back pain in former college rowers was no different to the general population. This suggests that a lumbar spine injury sustained in rowing does not necessarily have long term sequelae, but the rowers who are able to complete a rowing career un-injured are at lower risk of developing low back pain.

O’Kane et al., (2003) carried out a further survey on the same cohort as that examined by Teitz et al in 2002 and 2003 to determine if there is a significant association between pre-existing back pain and the development of back pain during a college rowing career. More subjects who had previous back pain before rowing developed back pain during their college rowing career than subjects without pre-existing pain (57.1% compared to 36.6%).

Although all these surveys were retrospective, with associated recall and response rate bias, they are the first to establish a comprehensive profile of lumbar spine injury and rowers. The studies suggest that a number of factors such as volume of ergometer training may be associated with the onset of low back injury and raise questions regarding injury predictors, which should be addressed in a more robustly designed prospective study.

A number of the studies reviewed so far, cite factors which were associated with the injury onset, which the authors linked to causation. However, these factors are actually reported as an activity which the rower was doing at the time of the injury onset and cannot be reported as causing the injury. ‘Sometimes the inciting event for an injury occurs distinct from the outcome event when the injury is actually observed –for example, an overuse injury’ (Hodgson et al., 2007). Previous studies in the general population (Hincapie et al., 2008 and Turner et al., 2008) and the sporting population (Greene et al., 2001) have identified pre-existing back pain as one of the best predictors of future injury which concurs with the finding of Teitz et al., (2003) and O’Kane et al., (2003), which were studies which aimed to identify a predictor for rowers’ lumbar spine injury. However, there is a need to examine predictors for lumbar spine injury in rowers more robustly.

The studies examining injury in rowing are summarised in table 1.1.

| Authors | Type of study | Sample size | Participants | Severity of injury measured? | Training and competition exposure measured? | Injury rate / 1000 hours. | Injuries classified? | Mechanism of injury reported? | Most common injury site | Factors associated with injury onset |
|-------------------------------------|--|-------------|-----------------------------|------------------------------|---|----------------------------------|----------------------|-------------------------------|---|--------------------------------------|
| <i>Budgett & Fuller 1989</i> | Retrospective survey of all injuries, 1 year. | 69 | International male rowers | Yes | Training estimated | 0.4(rowing) 4 (land training) | Yes | Yes | Lumbar spine (51%) | Weight training |
| <i>Boland & Hosea 1991</i> | Retrospective survey of all injuries, 3 years. | 180 | College male rowers | No | No | not measured | Yes | No | Knee (25%) | Not measured |
| <i>Smoljanovic et al 2009</i> | Retrospective survey of all injuries, 1 year. | 398 | International junior rowers | Yes | Yes | 2.1(training) | Yes | Yes | Lumbar spine (32.3%) | More than 7 training sessions / week |
| <i>Devereaux & Lachman 1983</i> | Prospective survey of clinic attendance, 2 years | 1186 | Recreational athletes | No | No | not measured | Yes | No | Lumbar spine (2.4% of total) | Not measured |
| <i>Parkkari et al 2004</i> | Prospective survey of all injuries, 1 year | 3363 | General population | Yes | Classed as 'participation time' | 1.5, 95% CI 0.6-3.9 | Yes | Yes | Not reported | Not reported |
| <i>Reid et al 1989.</i> | Retrospective survey of clinic attendance, 4 yrs | 275 | International female rowers | No | No | not measured | Yes | Yes | Lumbar spine (25%) | Time of year and weight training |
| <i>Coburn & Wajswelner 1993</i> | Retrospective survey of clinic attendance, 1 yr | 54 | Elite rowers | No | No | not measured | Yes | Yes | Lumbar spine (45% of total) | Weight training |
| <i>Hickey et al 1997</i> | Retrospective survey of clinic attendance, 10 yrs | 172 | Elite rowers | No | No | not measured | Yes | Yes | Chest (22.6%) female Lumbar spine (25%) male | Time of year |
| <i>Edgar 1992</i> | Retrospective survey of clinic attendance, 5 weeks | 44 | International junior rowers | No | No | not measured | Yes | No | Lumbar spine (30% of total) | Not reported |

Table 1.1: Summary of studies examining injury in rowers.

1.3.3. Summary of section 1.3.

There are a limited number of studies which have examined injury in rowers, all of which show methodological limitations. There is clearly a need for a prospective study to establish injury profile in rowers. Such a study requires training and competition details to be collected to allow injury incidence and predictors for injury to be ascertained. However, a consistent finding in the majority of studies is that lumbar spine injury, or 'low back pain' is a common problem for rowers. It is necessary first to understand the prevalence and possible causes of low back pain in the general population and then to apply this knowledge to the special population of rowers, by reviewing the appropriate literature. The aim of section 1.4 is to review the epidemiology, risk factors and pathophysiology of low back pain in the normal population.

1.4 Low back pain.

Low back pain is the term which is most commonly used to describe pain which originates in the lumbar spine region. It may be defined as

‘Pain and discomfort, localised below the costal margin and above the inferior gluteal folds, with or without referred leg pain’ (Airaksinen et al., 2006).

It is often divided in the literature into either acute or chronic low back pain, depending on the amount of time which the individual has had symptoms. Chronic low back pain is defined as pain persisting for at least 12 weeks and acute low back pain is that which has been reported for less than 12 weeks (Airaksinen et al., 2006). It is frequently multi-factorial although many studies group different pathologies together under the term ‘non-specific low back pain’. This section will examine epidemiology of low back pain, common pathologies which cause low back pain and risk factors for low back pain.

1.4.1 Epidemiology of low back pain.

In the USA, back pain is the most common cause of activity limitation in people under 45 years and the second most frequent cause of visits to a doctor (Andersson, 1999). The prevalence of chronic low back pain (CLBP) appears to be rising with continuing high levels of disability and health care use (Freburger et al., 2009). Freburger et al., (2009) found a point prevalence of 10.2% (95% CI 9.3 to 11%) of CLBP in 5357 adults in 2006 compared to 3.9% (95% CI 3.4 to 4.4%) in 1992. Palmer et al., (2000) showed that a one year prevalence of low back pain in a population increased from 36.4% in a population of 2667 subjects in 1988 to 49.1% of 10,363 subjects in 1998.

The specific incidence of low back pain in the population has been measured in many studies although it is difficult to compare findings due to different injury definitions and different time scales of measurement. One of the most widely quoted studies (Deyo and Tsui-Wu, 1987) examined the cumulative life time prevalence of low back pain in 10,404 subjects who all completed a questionnaire and underwent a physical examination. The definition of injury for low back pain was defined as ‘pain in your back on most days for at least 2 weeks’ and thus excluded subjects who had an incident of low back pain that lasted less than this time. Subjects were asked if they had ever had a low back pain episode at any

time in their life. The reported cumulative lifetime prevalence of low back pain (lasting at least 2 weeks) in this survey was 13.8% for the whole population. The number of subjects that reported back pain over the previous 12 months represented 10.3% of the sample population. The point prevalence of low back pain in the study population was 6.8%. The lifetime prevalence was similar among men and women.

In a review of 15 epidemiological studies examining lifetime incidence of back pain in the population of the USA (Andersson, 1999) it was noted that prevalence ranged from 48.8% to 69.9% over a lifetime and point prevalence varied from 12% to 30.2%. Such figures are higher than reported by Freburger et al.(2009) and by Deyo and Tsui-Wu (1987), which is likely to be due to a lack of standardisation in injury definition and variations in gender, age, demographic and social profile of different groups measured (see risk factors below).

As discussed in previous sections, more accurate epidemiological data is obtained by prospective analysis or retrospective data collection over a short time period. Such methods help eliminate recall bias. George (2002) examined the incidence of low back pain in a population of 1131 subjects at baseline and then six months later. Questionnaires investigating presence, site, type and duration of pain were examined at both time points. The author did not specify a definition of low back pain but subjects were asked to mark on a body chart, the site of pain. Thus all reports of pain, however short and low in severity were recorded. At the six month follow up, 8% of subjects (95% CI, 6 to 10.4%) reported an episode of low back pain in the time since baseline assessment. This finding seems high over such a time period, particularly when compared to the findings of Deyo and Tsui-Wu (1987), however, injury definitions were very different and the fact that this study had a retrospective element which demanded a 6 month recall may have affected accuracy in reporting.

Palmer et al. (2000) reported a 12 month (retrospective) prevalence of 49.1% which is very high compared to previous data. However, when data was analysed to only include those subjects who reported 'low back pain making it impossible to put on hosiery' only 2.7% of the cohort reported pain of this severity. This highlights how the definition of low back pain from the outset intrinsically alters the study results. This is also a factor when considering data collected by Croft et al., (1999) who recruited 2715 adults to report new episodes of back pain over a 12 month period. A mean of 25.3% of male subjects and 25.3% of females reported a new episode of low back pain in that time period. Again this

is high compared to previous reports but low back pain was defined as pain lasting for 24 hours or more. This may be compared to a survey of 31,044 adults (Deyo et al., 2006) which examined incidence of low back pain lasting at least 24 hours finding a rate of 26.4% in the study population. This study retrospectively examined the previous 3 months.

Thus while it is clear that low back pain is a problem for society, the exact incidence is unclear. This is due to varying recruitment procedures for subject samples and no standard definition given for low back pain. The studies divide the results further into lifetime prevalence, point prevalence and 12, 6 and 3 month prevalence. Therefore, to accurately compare data regarding low back pain, a standard or similar definition should be used as well as a comparable time period to allow accuracy. It appears that low back pain which is severe enough to last more than 2 weeks affects a small percentage of the population whereas a much higher proportion are affected by pain which appears to be self limiting over a short period of time.

1.4.2 Risk factors for low back pain.

Many studies which have examined incidence of low back pain also examined associated factors which may have influenced the onset of the condition. Such factors are reported to be 'risk factors'. The term 'risk factors' is used widely in literature related to both injury surveillance (see section 1.3) and musculoskeletal disorders such as low back pain although it may be argued that this term is misleading.

Croft et al., (1999) in the previously discussed study of 2715 adults also established a number of factors that were predictors of a new episode of low back pain. They found that poor 'general health' (self rated, compared to peers) was the strongest predictor of a new episode of pain (men, RR1.5, 95% CI, 0.8 to 2.7; women, RR 2.2, 95% CI, 1.2 to 4). High weight was associated with low back pain in women (RR 1.4, 95% CI, 1 to 2) but not in men. Levels of activity and occupation were not predictors of a low back pain episode. However, these results should be interpreted with some level of caution as all were self reported and assessed via a questionnaire and may have been subject to errors such as accuracy in reporting weight in men. Self rating of 'general health' may have introduced error as this could see variation in interpretation. Some individuals may have been unaware of their poor health status due to lack of education and also may be affected by psychological factors such as self esteem issues.

Adams et al., (1999) carried out a prospective study of 403 health care workers to examine risk factors for low back pain. All were aged between 18 and 40 years and had no history of 'serious' back pain at the outset. At baseline, all completed questionnaires investigating psychological factors. Physical measures were also carried out to measure: back muscle strength; quadriceps strength; back muscle fatigueability; lumbar lordosis and range of motion (flexion, extension and side flexion); sacral inclination and ranges of hip flexion; peak spinal loading during standardised lifts; and anthropometry. The subjects were questioned (via postal questionnaire) about any new incidence of back pain at 6, 12, 18, 24, 30 and 36 months following the baseline. Over the period of the study, 90 subjects reported 'serious' (required medical attention or time off work) back pain and 266 reported 'any' back pain. The consistent predictors of serious back pain were: reduced range of lateral flexion; a long back; reduced lumbar lordosis; increased psychological stress; and previous history of non serious low back pain. However, it must be noted that less than 12% of the study population could attribute their back pain to the predictors that were highlighted. It is also pertinent that this study did not find that back muscle strength had significant influence of low back pain onset although the rate at which the muscles fatigued did have some influence (reported for serious low back pain, reported at 36 months, $P=0.01$). The authors suggest that this is likely to be due to the nature of the health workers job which often required repeated, sustained lumbar flexion which leads to tissue 'creep'. While a criticism of this study is that it may have observed a biased sample of young health care workers, it examined a comprehensive number of factors which have previously been suggested to lead to onset of back pain. The results may not be usefully generalised to the standard population but it highlights the fact that the causes of low back pain are multifactorial and may not be attributed to a small number of factors.

While Croft et al., (1999) and Adams et al., (1999) both underlined the fact that causation of low back pain is complex, involving multiple factors, a number of studies have concentrated on lifestyle factors and their influence on low back pain onset. The studies which have received particular attention relate to obesity and smoking. However, as neither of these factors is likely to be strongly linked to the onset of back pain in rowers, they will not be discussed in this thesis.

It appears from the literature that there is very little clarification regarding the risk factors for low back pain. The studies in many cases are flawed, in that when causation is not established with reference to Hill's criteria (Hill, 1965), the factors should not be termed

'risk factors' but more appropriately described as associations. Methodological factors in studies, consistently affected quality of findings and reduce the ability to compare studies. As with the epidemiological studies outlined above, multiple definitions of low back pain and various methods of reporting mean that comparison of findings are not possible. There is a need for large longitudinal studies which investigate risk factors individually before conclusions may be made.

1.4.3 Pathophysiology and classification of low back pain.

As stated earlier, low back pain is frequently multi-factorial and single specific causes of low back pain are not common and are as low as 15% or less, of all reported back pain (Airaksinen et al., 2006). However, McGill, (2002) argues that this is a likely underestimation and may be a reflection of poor diagnosis or understanding of causation.

Low back pain is frequently classified, particularly for research purposes, into 3 categories which were described by Waddell (1987) as:

- Specific spinal pathology.
- Nerve root pain / radicular pain.
- Non-specific low back pain.

The pathophysiology of low back pain may be divided into *extrinsic* and secondary conditions or *intrinsic* and primary conditions of the spine (Bartleson and Deen, 2009).

Extrinsic conditions.

Bartleson and Deen, (2009) list the extrinsic conditions which cause pathophysiology in the spine as: trauma; bacterial infections; viral infections; fungal and parasitic infections; inflammatory demyelinating myelopathies; toxic, metabolic and hereditary myelopathies; vascular myelopathy; and tumours. The conditions which are most associated with sports injury in this list are those due to trauma. This occurs in its most catastrophic form in the form of spinal cord injury which is seen in sports such as rugby and horse racing (Bartleson and Deen, 2009).

Intrinsic conditions.

Extrinsic conditions are a cause of only a very small number of spine conditions as most are due to conditions which may be congenital or acquired and affect the spinal column

and its component parts which are thus intrinsic. It is likely that lumbar spine injury to rowers would be classed as acquired intrinsic conditions as they are caused by damage due to cumulative loading or trauma to the structures described below.

Intervertebral discs.

Discs change over time, showing signs of degeneration. Intervertebral disc degeneration is characterised by structural damage to the disc matrix combined with increased activity of matrix degrading enzymes. The discs show marked decompression of the nucleus so the annulus bulges radially and loses height and high stress concentrations develop in the degenerated annulus causing tears or fissures (Adams and Roughley, 2006). The main cause of disc degeneration is increasing age, but it is also thought that a genetic inheritance may be to blame. Battie and Videman (2006) state that some discs become so weakened by suboptimal genes and aging that the matrix becomes damaged during normal every day activities explaining why it is so common in the lower lumbar spine which is most heavily loaded and why it is more prevalent in athletes and manual workers. The greatest risk factor for disc injury was believed to be cumulative loading; a concept which held for many years. However, this theory is now being challenged; Videman et al., 2010, demonstrated that cumulative loading because of higher body mass was not harmful to the discs and that a slight delay in L1-L4 disc desiccation was observed in heavier men compared to their lighter twin brothers. This appears to challenge the cumulative injury model of disc degeneration which has been extensively quoted in reference to areas such as occupational lifting injury. The authors note the limitation of this study in that excess body weight is used as a surrogate for lifting, however, it indicates that further research is required to understand risk factors for disc injury.

Degenerated discs are often painful which is thought to be caused by nucleus tissue which chemically irritates the nerves in the outer annulus (Olmaker, 2008). The most common cause of severe back pain is a complete radial fissure which extends from the periphery of the disc to the nucleus (Adams and Roughley, 2006). Discs may also herniate (also called rupture or prolapse) which can cause compression of the spinal cord or spinal nerve. A disc herniation is defined as a 'localised displacement of disc material beyond the limits of the intervertebral disc space' (Bartleson and Deen, 2009). When discs herniate, pain sensitisation can occur which affects nerves in the outer annulus and nerve roots and causes back pain and sciatica. While physical entrapment of a nerve root causes paraesthesia, it is now accepted that chemical 'sensitisation' which is a type of

inflammation is needed to generate back and leg pain (Adams, 2009). Kuslich et al., (1991), examined the tissue origin of low back pain in 193 consecutive patients and found that the outer annulus is the tissue of origin in 'most cases of back pain'. While the exact cause of discogenic pain is not fully understood, recent research links its source to neo-innervation of degenerative discs (Garcia-Cosamalon et al., 2010, Fagan et al., 2010 and Edgar, 2007). Garcia-Cosamalon et al., 2010, note that the normal disc is a poorly innervated organ although degeneration results in the disc annulus becoming densely innervated with associated pain. The mechanisms associated with neo-innervation are not clear but it is thought to be linked with increased levels of neurotrophins which are observed in pathological discs. Some of the ideas regarding discogenic pain involve a degree of speculation and further research is required to clarify such theories.

Ligaments and muscles.

The ligaments of the lumbar spine may be damaged as a result of trauma and can lead to excessive mobility. The ligamenta flava and posterior longitudinal ligament can become ossified and thickened with age, causing them to encroach on the spinal canal and leading to altered biomechanics and subsequent pathology (Bartleson and Deen, 2009). Kuslich et al., (1991) illustrated that the posterior longitudinal ligament can frequently be tender and is a source of central low back pain; however it is not clear if this is because of its close proximity to the annulus fibrosus of the disc. Muscles are not a common source of lumbar spine pain, they are not sensitive to provocation tests and pain in the area of a muscle may be derived from local vessels and nerves rather than the muscles themselves.

Bones and joints.

Bartleson and Deen, (2009) outline a number of changes that take place in the vertebrae and associated joints which may lead to pain. Bony spurring can occur at the superior and inferior part of the vertebra as well as the uncovertebral joints which can lead to nerve root impingement. Degenerative changes in the disc can increase strain on the facet joints and associated capsule and ligaments leading to degenerative changes here also. These degenerative changes may cause the neural and spinal foramina to be compromised. Kuslich et al (1991) found that the facet synovium is not a source of pain although the facet capsule is 'sometimes tender' and that the true significance of the facet joint in the production of low back pain is in its ability to compress or irritate the nerve root and annulus. Inflammatory disorders such as rheumatoid arthritis will affect the joints of the lumbar spine causing pain in this region. Osteoporosis and other bone diseases will cause

structural changes in the spine and are associated with varying intensities of pain, depending on the stage of the disease and associated sequelae such as fractures. Other than such systemic disease, Kuslich et al., (1991) showed that spinal bone was not a source of pain.

Congenital anomalies.

Bartleson and Deen (2009) state that about 5% of the population have a congenital anomalies in their spine, the most common being spina bifida occulta. Other common anomalies are sacralisation (4 lumbar vertebrae) or lumbarisation (6 lumbar vertebrae). Spinal stenosis may be congenital or acquired and is caused by a narrowing of the spinal canal either congenitally or as a result of degeneration. Spondylolysis (a defect in the pars interarticularis) or the associated spondylolisthesis (slippage of one vertebra on the adjacent due to a bilateral pars defect) may be congenital or acquired.

Despite knowledge of the wide range of conditions which may lead to pain in the lumbar spine, pathology and radiological findings are poorly correlated in patients with low back pain symptoms (Airaksinen et al., 2006). Low back pain is not attributable to specific pathology or neurological encroachment in about 85% of people (Deyo, 1988). Thus, the number of low back pain patients presenting with specific, distinct pathology are unusual and the majority of cases (around 85%) will be classified as having non-specific low back pain (Airaksinen et al., 2006).

1.4.4 Summary of section 1.4

Low back pain is a common problem in society although the exact prevalence has not been clearly defined. Reports of lifetime prevalence range from 13.8% to 69.9% of the population while point prevalence varies from 10.2% to 30.2%. Various risk factors have been described for low back pain. Poor general health, psychological factors including stress, obesity and smoking have all been cited to increase risk of developing low back pain. Consistent problems in study methods mean that reported results should be viewed with caution. The many various definitions of low back pain between studies mean that low back pain of 24 hours duration is compared with that which lasts '2 weeks or more', meaning that very different presentations of the same, broadly termed, condition are being compared. Also, the term 'risk factor' is consistently used in studies although no causation is established in any study. There is a clear need for further studies which are based on a

standard definition of low back pain and examine risk factors separately to try to establish causes.

The use of the definition 'low back pain' is an umbrella term which encompasses many different pathological presentations. Low back pain is frequently classified either by symptomatic presentation or by the structure which is the predominant source of pain. Even with such sub classifications, the term 'non – specific low back pain' is the one most frequently used. While the pathophysiology may be divided into intrinsic and extrinsic factors, only a small percentage of the low back pain population will experience relief of symptoms by addressing a simple pathological source, such as a disc protrusion. The causes of low back pain are not well understood and it is pertinent to consider that it is simply a symptom which lacks consensus and invites extensive debate.

To understand the processes which cause tissue failure or development of pathology in the lumbar spine, it is necessary to consider a number of factors. The functional anatomy of the lumbar spine needs to be analysed to understand how its component parts function normally. The kinematics of the lumbar spine and forces acting on the low back, particularly under conditions of loading, explain how repeated or altered motion patterns lead to development of low back pain. These factors will be reviewed in the following section.

1.5 Functional anatomy and biomechanics of the lumbar spine.

The following text will review the anatomy and biomechanics of the lumbar spine with reference to function and development of pathology. However it is important to note that good understanding of lumbar spine injury means that the lumbar spine should not be considered in isolation when examining motion characteristics. McGregor and Hukins, (2009) emphasise the importance of considering the function of the spine in the context of the whole body, especially the lower limbs. There is considerable evidence that the joints of the lower limbs, notably the hips, are involved in spinal function (McGregor and Hukins 2009, Shum et al., 2005) and failure to understand the role of the other body segments in the clinical setting may result in a poor understanding of the complexity of low back pain.

1.5.1 Functional anatomy of the lumbar spine

The vertebrae

The vertebrae of the lumbar spine are constructed well to withstand forces of every day activities. The vertebral body is constructed to withstand longitudinally applied loads and is constructed like a barrel with round walls of stiff cortical bone and is covered at the superior and inferior surfaces by the deformable cartilage end plate which is porous for transport of nutrients. The interior of the vertebrae is filled with cancellous bone which has a trabecular arrangement which is aligned with stress trajectories that develop during activity (McGill, 2002). The posterior elements of the lumbar spine consist of the pedicles, laminae, spinous processes and facet joints. The inferior articular processes project downwards to articulate with the superior articular processes of the vertebra below forming a synovial joint which has a main function to provide a locking mechanism that resists forward sliding and twisting of the vertebral bodies (Bogduk, 2005). The spinous and transverse processes provide areas for muscle attachments.

The intervertebral joints.

The joints between the vertebrae are composed of the articulations between the 2 vertebral bodies (interbody joint) and the articulations between the superior articular process of one vertebra with the inferior articular process on the one above, this is known as a zygapophysial joint (or facet joint)

The lumbar facet joints vary in shape and orientation; some are predominantly flat and some are more curved. Some of the joints are orientated more to the transverse plane and some more to the sagittal plane. The closer the joint is orientated to the sagittal plane, the less it is able to resist sagittal plane motion (flexion) although such joints resist rotation strongly. Articular cartilage covers the facets and is thickest over the centre of the facet, resting on a layer of subchondral bone (Bogduk, 2005).

The interbody joint is formed by the articulations of 2 vertebral bodies, separated by the intervertebral disc. The intervertebral disc consists of an outer annulus fibrosus and an inner nucleus pulposus. The top and bottom of the disc are covered with a layer of cartilage called the vertebral endplate. The nucleus is made of a gel like substance which has an elastic response when it is deformed. The nucleus is 70-90% water. The annulus consists of collagen fibres arranged in concentric rings called lamellae. In each successful lamellae, the orientation of the collagen fibres alternates and measures about 65 to 70 degrees from the vertical (Bogduk, 2005).

Function of the disc.

The function of the disc is to allow movements between the vertebral bodies and it acts as a hydrostatic structure that allows 6 degrees of motion between the vertebrae (McGill, 2002). The annulus and nucleus work together to sustain compressive loads. Dolan and Adams, (2001) have identified 3 factors that can increase compressive load bearing by the neural arch: pathological disc narrowing; prior long term 'creep' loading; and lordotic postures. Under spine compression, the nucleus pressurises, applying hydraulic forces to the end plates vertically and the inner annulus laterally, causing the annulus fibres to bulge and become tensed (McGill, 2002). While there was a conception for a long time that the highest compressive stress lay within the nucleus, stress profilometry has shown that in most discs, the highest compressive stresses usually appear in the middle of the annulus, posterior to the nucleus (Dolan and Adams, 2001). Pressure measurements in the disc have been conducted *in vivo* in various postures and functions of daily life. Wilke et al., (1999) conducted intradiscal pressure measurements in one volunteer performing various activities. A pressure transducer was implanted into the nucleus pulposus of a non-degenerated L4/5 disc of a male, 45 year old subject, pressure was recorded with a telemetry system over a 24 hour period measuring a number of activities. Pressure in the disc measured from as low as 0.1MPa in prone lying to a maximum reading of 2.3MPa when lifting a 20 kg weight with round flexed back. It was also noted that during 7 hours

of sleeping, pressure in the disc increased from 0.1 to 0.24 MPa. This study is limited in its application to the general population in that it only measured one subject and only one disc but it provides important information regarding postural effects on the disc. When the cadaveric spine is loaded in combined flexion and compression, 70% of the bending moment is resisted by the intervertebral ligaments and around 30% by the disc. In extension, 2/3 of the bending moment is resisted by the neural arch and 1/3 by the disc (Bogduk, 2005).

Ligaments of the lumbar spine.

The ligaments of the lumbar spine consist of the ligaments that connect intervertebral bodies, those that connect the posterior elements, the iliolumbar ligaments and 'false' ligaments. The anterior and posterior longitudinal ligaments connect the intervertebral bodies and resist separation of such. The ligaments of the posterior elements are the ligamentum flavum, interspinous ligaments and supraspinous ligaments. The ligamentum flavum is a thick band which joins the laminae of each vertebra and is high in elastic fibres (80% elastin, 20% collagen). The interspinous ligaments connect the spinous processes and resist separation of the spinous processes but offer limited resistance to sagittal flexion of the spine. The supraspinous ligaments bridge the interspinous spaces. The iliolumbar ligament prevents forward sliding of the L5 vertebra on the ilium. The false ligaments consist of the intertransverse, transforaminal and mamillo-accessory ligaments and are small ligaments that have limited function (Bogduk, 2005).

Considering the role of the ligaments, (McGill, 2002) states that the principal ligament for resisting flexion is the supraspinous ligament. When cadaveric motion segments are compressed and flexed in a loaded position, 70% of the moment is resisted by the intervertebral ligaments. The ligaments play a limited role in extension although the ligaments of the facet joints may resist hyperextension (Dolan and Adams, 2001).

Muscles of the lumbar spine.

The small muscles of the lumbar spine are the rotators and intertransversarii; the rotators are involved in rotation and the intertransversarii in side flexion. The major extensors of the lumbar spine are the longissimus, iliocostalis and multifidus. The latissimus dorsi is also involved in creating extensor torque as it originates at the lumbar spinous processes although it attaches to the humerus (McGill, 2002). However, lumbar extension is complex and the thoracic extensors are actually the most efficient lumbar extensors as they

have the largest moment arms and pass over the lumbar region. What are regarded as the lumbar extensors (i.e. located in the lumbar region) only contribute a small amount to lumbar extension (McGill, 2002).

The flexors of the lumbar spine are the abdominal muscles and the psoas. The rectus abdominus is the major trunk flexor. The 3 layers of the abdominal wall which are the external and internal oblique and the transverse abdominus are also involved in flexion. The obliques are also involved in trunk rotation. The obliques and transversus form a containing hoop around the abdomen along with the abdominal and lumbodorsal fascia which aids spine stability (McGill, 2002).

1.5.2 Kinematics of the lumbar spine

Measurement of spinal kinematics has concentrated on range of motion analysis using a number of methods. These methods comprise radiographs, magnetic resonance imaging (MRI), computerised tomography (CT), electrogoniometers and videofluoroscopy (Li et al., 2009). In addition to these methods, dynamic assessment of spinal kinematics is also performed using laboratory based motion analysis systems (McGregor, 2003).

The movements of the lumbar spine are flexion and extension in the sagittal plane, side flexion in the frontal plane and a small amount of axial rotation in the horizontal plane. All lumbar joints have a similar range of total motion in the sagittal plane although the middle intervertebral joints have a greater range of flexion and the higher and lower joints have relatively greater extension. However, pure movements in single planes are not observed and motion is coupled. For example, flexion of lumbar vertebral joints involves a combination of anterior sagittal rotation, forward translation as well as a small amount of axial and frontal plane rotations as well as some vertical and lateral translations. Similar coupling of motion planes are seen for other vertebral movements although the degree of coupling varies between individuals (Bogduk, 2005).

There is little information available concerning range of motion at different segments which is limited in accuracy in some cases, as analysis was performed on cadaveric tissue. A clearer picture is given by a combination of videofluoroscopy and MRI as a dynamic picture is produced. Such methodology was used in a recent study (Li et al., 2009) to ascertain segmental vertebral motion during functional human lumbar spine activities. Subjects were imaged in standing and various degrees of flexion, extension, side flexion

and axial rotation. Images were taken at L2-3, L3-4 and L4-5 levels. The greatest range of motion was seen in flexion with the L4-5 level showing a smaller movement range (1.9° (1.1)) than the other levels (L2-3 = 5.4° (3.8), L3-4 = 4.3° (3.4)). Motion in the frontal plane (side flexion) was greatest at L4-5 (4.7° (2.4)) than L3-4 (3.4° (2.1)) and L2-3 (2.9° (2.4)). Axial rotation was small and was not significantly different at each level (L2-3, 2.5° (2.3); L3-4, 2.4° (2.6); L4-5, 2.9° (2.1)). All primary movements were accompanied by coupled movements in all remaining degrees of freedom. This study was limited by the fact that flexion was not measured at maximal flexion (only 45°); however it provides a valuable assessment of the various contributions of the different spinal levels to movements.

1.5.3 Summary of section 1.5

The vertebrae, joints and discs of the lumbar spine are well constructed to withstand loading associated with every day activity. Ligaments resist separation of various components of the vertebrae and movement is provided by activity of a number of muscle groups working together. The movements of the lumbar spine comprise flexion and extension in the sagittal plane, side flexion in the frontal plane and a small amount of axial rotation in the horizontal plane. Movements occur in a coupled fashion during normal every day activities.

To further understand the mechanics which leads to injury in the lumbar spine of rowers, it is necessary to review literature which examines kinematics, loading and muscle activity in this group to consider why such an activity may lead to tissue failure in structures which are apparently well designed to sustain force. This will be done in section 1.6.

1.6 Spinal kinematics, loading and muscle activity of the lumbar spine in rowing.

The measurement of spinal motion in rowing has attracted limited attention and has focussed on 2 specific aspects; kinematics and muscle activity. A search was carried out using the terms: *rowing; rowing injury; rowers; rower's injury; injury + rowing; injury+ rowers; rowing kinematics; rowing biomechanics; rowing and lumbar spine; rowing ergometer*. The search engines of Embase, Pubmed, Cinahl, Science Direct, Google Scholar, AMED and Web of Science were investigated. The final search was carried out in December 2009. All published studies that were accessed involved measurement of

rowers on ergometers, in a laboratory. An extensive search of medical and scientific literature could not find any research which had analysed motion of the lumbar spine in a boat, on the water. Of the 24 studies that were accessed, 10 were excluded as they did not examine spinal activity. Of those remaining, 9 examined spinal kinematics, 1 examined forces on the lumbar spine and 4 examined muscle activity.

1.6.1 Spinal kinematics in rowers.

Various measurement methods have been used in measurement of kinematics of the rower's lumbar spine.

McGregor et al., (2002) used interventional MRI to assess intersegmental motion and pelvic tilt in elite oarsmen. MRI is useful for measuring spinal orientation as motion segments are clearly viewed and not affected by skin movements over a bony point. However, the static nature of MRI means that it gives no dynamic data. Interventional MRI is 'real time' imaging which is used to provide images during activity such as surgical procedures or 'interventions'. Interventional MRI allows subjects to be placed in functional positions, which gives more meaningful results. McGregor et al., (2002) investigated spinal and pelvic mobility in a group of elite oarsmen with and without a history of low back pain. Twenty subjects (9 with no history of back pain, 4 with current back pain and 7 with a history of back pain) were scanned using an Interventional MRI scanner. An MRI compatible rowing jig was constructed which permitted the simulation of 4 stages in the rowing stroke within the scanner; the catch, finish, early and late drive phases. The subjects were asked to adopt each position in sequences and pull on an oar to load the spine. All images were assessed in the sagittal plane. Measurements of the angle formed between each of the lumbar discs and angle of lumbar and sacral inclination were assessed.

Results showed different spinal and pelvic positioning between the 3 groups of rowers. The main finding was that rowers with either current or previous low back pain presented with hypomobility of the lumbar spine when compared to those with no history of low back pain. The rowers with no history of back problems presented with greater rotation of the lumbar spine into flexion at the catch, returning to a neutral upright position at the finish. Rowers with either current or previous back pain presented with stiffness in the lower lumbar spine and gained range by flexion at the upper lumbar or lower thoracic spine. At the catch, all rowers held their lumbar spines upright relative to the sacrum which was held

in anterior tilt. All rowers except those with a current back problem flattened their lumbar lordosis which was explained by the fact that those with a current back pain problem showed significant loss of angulation at L5/S1 ($P<0.05$) and L1/2 ($P<0.01$). The area of greatest lumbar intersegmental motion at the catch for all groups was seen at L4/5 although there was a difference of 1° between that and motion of the other segments in the control group. During the drive phase rowers held their lumbar spine in an upright vertical position although those with current back pain started to extend their lumbar spine relative to the sacrum. At the finish, rowers with current low back pain extended their lumbar spine and rotated their sacra and pelvises posteriorly compared to the control subjects who held their lumbar spines in a neutral position ($P<0.05$). All lumbar joints showed similar ranges of intersegmental motion in the control group.

The merit in this study lies in the accuracy of recording spinal motion and it has provided valuable information regarding movement at individual spinal segments in the rowers. However, the static nature of MRI means that the findings may not translate to rowing on an ergometer or boat which is a dynamic activity. The most significant differences in this study were found in rowers who currently had back pain although the pathology and associated inflammation of an acute condition may have made it difficult for the rowers to take part correctly in the tests and may have altered the findings. A succinct appraisal would be that these findings do not suggest that altered motion patterns lead to low back pain but are as a result of pathology which is causing pain and limiting movement. It may have been better to exclude this group and to analyse rowers only with a previous history of pain or, ideally, to conduct a prospective study on a large cohort to assess which motion patterns are associated with onset of low back pain

Bull and McGregor, (2000) recognised the static limitations of MRI and thus validated an electromagnetic device (Flock of Birds) against MRI. The Flock of Birds would allow dynamic measurement to be assessed. Six elite, male rowers comprised the subjects who had receivers from the system fixed at the 12th thoracic vertebra, the sacrum and the femur. The rowers completed a 10 minute rowing piece at 'maximum effort' on the Concept 2 ergometer and were then asked to row for short time periods replicating 3 different 'poor rowing technique' variants. Samples of data were collected at different points of the cycle. An MRI evaluation was conducted to quantify the relative motion between the receiver mounting blocks and the spine which is a measure of the skin relative to the bone. A

custom designed device was made to allow the spinal position of the rowers to be set at different stages of the rowing cycle in an interventional MRI scanner. The lumbar spine and pelvis were imaged in the sagittal plane in the mid point of the spinous processes at the catch and finish position of the rowing stroke, and the orientation of the mounting blocks relative to the spine were measured. Scans were then taken with the rower pulling hard on the oar to simulate rowing. Kinematic data were recorded for 3 body segments; the femur, pelvis and thorax.

The average error in measuring spinal flexion/extension was $\pm 1^\circ$ (SD 1.0° , $N = 6$) when the orientation of the mounting blocks was compared to the spinal orientation in MRI. The authors concluded that the electromagnetic device is a valid tool to measure spinal motion in rowers. Variations in the lumbosacral and thoraco-lumbar angles during the different rowing styles and phases of the stroke were noted. It was observed that as fatigue set in, control of rotation of the pelvis 'deteriorated' with greater increased posterior pelvic tilt throughout the stroke, particularly in the late drive phase and at the finish. When good technique was compared to poor technique, significant differences were noted in the angle of the pelvis on the femur, particularly in the first phase of the drive, demonstrating that the electromagnetic device was sufficiently accurate to discern minor differences in technique and motion patterns. As in the previous study, only sagittal plane motion of the spine was measured, although the authors suggest no movement takes place in other spinal planes while on a rowing ergometer. Studies are needed to confirm this statement.

The two studies reviewed so far analysed rowers' spines statically or over a short time period of rowing, which does not realistically replicate training or racing. McGregor et al., (2005) designed a study which used the electromagnetic system already validated, to analyse the spinal kinematics of rowers' lumbar spines in a dynamic setting. Twelve female rowers who were part of the British National Team performed an incremental 'step test' which is used routinely to measure physiological parameters in rowers. Testing was performed on a Concept 2 rowing ergometer and comprised of 5 steps, each step performed at a different stroke rate and power output. Each step lasted 4 minutes and increased from an initial stroke rate of 18 per minute, finishing at 28 strokes per minute. Kinematic analysis of the lumbar spine was performed using the Flock of Birds measuring device. The receivers were attached to the skin over T12/L1, at L5/S1 and 10 cm above the lateral condyle of the femur. Movement was recorded as rotation on the sagittal plane. A load cell was also placed on the handle of the ergometer to measure tensile forces at the

handle during the stroke and a motion sensor determined the handle position in space. At the end of the step test, the rowers performed a 2 minute maximal rowing test. Data analysis was performed and the rowing cycle was divided into phases where 0% represented the catch position of a stroke with the onset of tensile force production and 100% represented a full stroke cycle and return to this position.

Significant differences in peak force were observed between the first and last step of the test ($P < 0.0001$) and the point at which the peak force developed became later in the stroke at higher ratings. At the catch, anterior pelvic rotation occurred which decreased in magnitude at higher ratings. At the finish, posterior rotation of the pelvis occurred and the magnitude of the rotation increased with increasing steps. This demonstrated that the lumbo pelvic region became relatively more flexed as the test progressed. A greater magnitude of lumbar flexion compared with pelvic flexion was observed at the catch and at the finish; greater magnitudes of lumbar extension were seen than pelvic rotation. The authors suggested that the rowers were 'under-utilising' pelvic motion compared to lumbar motion. The point at which peak force developed varied between 13.7% (2) of the cycle in the 1st step to a mean of 16.3% (1.9) of the cycle which was close to the point of maximum anterior rotation of the pelvis. When the step test was compared with the maximal test, a number of differences were observed in the maximal test; the stroke length was shorter, lumbopelvic rotation was smaller at the catch and the lumbar spine tended to 'over extend' at the finish.

This study showed the important changes in lumbar spine kinematics over a fatiguing protocol. It appeared that as the rowers became fatigued, their spine flexed more, particularly at the finish and this is likely to increase loading on the spine as muscle control and endurance decreased. This study highlights important kinematic changes which may predispose the rower to injury, particularly when fatigued.

A study that was similar in nature (Caldwell et al., 2003) examined the spinal kinematics of 16 school rowers (mean age 16.4 years, 8 males and 8 females) over a 2000 metre, maximal effort rowing test. Adhesive reflective markers were placed at L3 and S1 and a video camera set at a distance of 2m from the subjects recorded at 30 frames / second. Three consecutive rowing strokes at 20% (catch), 60% (mid drive) and 95% (finish) time points of the rowing cycle were analysed. The data was digitised with a motion analysis system (Expert 11, New Zealand). Range of flexion of the lumbar spine was analysed and

expressed as a percentage of full standing flexion which was measured prior to the test. Across the 3 stages of the rowing trial, lumbar flexion significantly increased at the catch and mid drive phase ($P<0.05$). Mean flexion at the catch at the beginning of the test was 80% of maximum standing flexion compared with 87% at the end, whereas flexion in the mid drive increased from 74% of maximum to 89% of full standing flexion. There were no differences in gender.

This study demonstrated that rowers exhibit high values of lumbar flexion which increases as they fatigue. As the flexed spine is loaded, particularly during the drive phase, this has clear implications for injury. As with previous studies, only sagittal plane was measured with its associated limitations and ergometer kinematics may not represent what happens when the rower is in the boat.

Studies reviewed so far have analysed motion of the lumbar spine either at multiple levels in static positions (Interventional MRI) or at 2 levels dynamically. A more comprehensive representation of lumbar kinematics is produced when measurements are performed at multiple levels of the spine. Pollock et al., (2009) examined the spinal kinematics of 9 female international rowers while performing a 2000m test on a Concept 2 rowing ergometer. Reflective markers were placed over the spinous processes of C7, T4, T7, T10, L1, L3 and S1 as well as the mid point of the iliac crest and at 7 markers on the upper and lower limbs. The 3 dimensional positions of the segments were tracked by a real time motion analysis system. Peak angular velocities of the motion segments were determined by the percentage of the stroke during which each segment showed the greatest change in position over time.

In the first 10% of the stroke all subjects displayed pelvic and lumbar segments moving from positions of flexion into extension. The lower lumbar segment reached peak angulation velocity at the beginning of the period of peak force production of the stroke. This means that the lower lumbar spine was extending quickly at this time followed by the pelvis. The pelvis was the main segment extending the trunk during the period of peak force production. The spinal segment which moved the most during this period was L3-S1. However, the spinal segments moved relatively little during this period compared to the pelvis. Towards the end of the drive phase the thoracic segments started to flex even though the pelvis was still extending. The pelvis moved through a mean of 40.9° (6) throughout the full stroke cycle, L3-S1 moved through 10.5° (3.1), and L1-L3 moved

through 8.6° (3.5). This study provides useful data regarding relative motion of spinal segments. It suggests that there is limited movement in the spinal segments and shows that the pelvis is where maximum motion takes place. While motion of the pelvis is an important part of flexion of the lumbar spine, it is likely that injury in rowers is seen in a number of different levels of the lumbar vertebrae so there is obviously value in also considering a number of lumbar levels. It should be noted that the sample was taken from early in the rowing session; spinal motion may change when supporting musculature fatigued later in the rowing session.

The studies reviewed so far have highlighted high levels of flexion in the lumbar spine which can reach as much as 89% of full standing flexion. Dissemination of these findings and prior knowledge of the high rate of lumbar spine injury in rowers has led rowing coaches to introduce programmes to improve stability of the lumbar spine. While McGregor et al., (2007) did not quantify what such a programme included, they assessed spinal kinematics of female international rowers two years after the original study described above (McGregor et al., 2005) following a time period when they had 'increased spinal stability work' in training. Seven of the 12 rowers who were tested originally were still rowing and completed the study.

The aim of the study was to examine if kinematics of the rowing technique assessed during a step test changed over time as a result of training and 'additional trunk strengthening work'. The protocol was exactly the same as that described previously. When the tests were compared, the peak force developed at the second test (test B) was significantly higher ($P < 0.01$) than the first test (test A) rising from a peak of 40N to 80N for the 5 steps indicating that the rowers had increased their strength. A non-consistent stroke length was observed in test A which was more stable by test B and showed a significant rise in overall stroke length ($P < 0.0001$). The lumbo-pelvic ratio at test A increased with each step, indicating a predominance of lumbar motion, but by test B this ratio had improved and become more consistent, indicating equal amounts of lumbar and pelvic motion. This finding means simply that the rowers have a more upright trunk position, which the authors indicate will reduce loading at the junction of the lumbar spine and pelvis.

This study, and the previous on the same cohort, focussed on 2 markers; one on the lumbar spine and 1 on the pelvis. It was therefore concerned with lumbopelvic motion and was not able to provide any information regarding different spinal segments. The author did not

report why 5 of the original subjects were no longer rowing. It was clearly shown that the 7 rowers in the second test were a stronger group with more stable lumbar spines and more efficient rowing technique compared to the mean findings of the first group. The results of this study would be more interesting if all of the original cohort were re-tested or if this cohort were re-tested 2 years hence. Review of injury patterns of the original subjects over the 2 years would help to establish if there was an association between spinal kinematics in this group and risk of lumbar spine injury.

The studies reviewed so far have shown that kinematics of the lumbar spine change as rowers fatigue. Literature reviewed earlier in section 1 highlighted the fact that rowers spend large amounts of time training on the ergometer and some injury studies have indicated that it may be implicated in lumbar spine injury. It is likely, therefore that rowers frequently train on ergometers to the point of fatigue. The studies examined so far have simulated race situations (2000 metre tests) or incremental loading (step tests) to examine physiological parameters. It is necessary to consider the behaviour of spinal kinematics over an extended time period which would more likely mimic a standard training session.

Two studies examined spinal kinematics over a 1 hour period of rowing. Holt et al., (2003) examined the lumbar spine kinematics of 13 elite, rowers over a one hour piece of rowing at a standard stroke rate and a heart rate maintained between 130 and 150 beats per minute. The electromagnetic system and receiver fixation in this test was the same as that described previously (Bull and McGregor, 2000). The ergometer was also instrumented with a load cell in line with the handle, connected to the chain that provided information about the tensile force developed at the handle. The lumbopelvic kinematics was sampled at the start of the session and at quarterly intervals throughout the hour piece. Data analysis showed a significant increase in maximum spinal flexion ($P=0.003$) between the first and last phase of the rowing piece. There was a smaller but significant ($P=0.04$) increase in maximum spinal extension. There was also a significant increase ($P=0.002$) in the phase of the stroke at which peak force was produced. This means that as the rower fatigued, their lumbar spine became more flexed, moved through a greater range of motion to allow them to achieve greater extensions, and took them longer to develop peak force in the drive phase.

Mackenzie et al., (2008) repeated this study some years later to examine if more skilled rowers (in this instance, male international rowers) would exhibit a different response to

the protocol due to their superior experience and fitness. The described protocol was repeated exactly by six rowers and this time, six data samples were collected at intervals throughout the test. In this case, no significant changes were seen in sacral rotation or lumbar spine flexion or extension angles over the one hour piece. An increase of lumbar flexion (mean of 1.4°) and extension (mean of 4°) were observed as were increases in anterior rotation of the pelvis at the catch (mean increase of 0.9°) and posterior rotation at the finish (mean increase of 7.4°) when the first phase and last phase of the test were compared. None of these changes were statistically significant. This indicates that the more experienced rowers exhibit greater lumbo pelvic and spinal stability possibly due to greater endurance of spinal muscles. However, the first study only read four data points compared to the second which read six; this could have affected data as the early stages of the first study may have simply measured a 'warm up' period. The warm up period was three minutes in the first study compared to five minutes in the second study which may have exaggerated findings in the original protocol. However, in both studies, fatigue was associated with increased spinal flexion and extension which may be a factor in the generation of back pain in rowers.

All of the studies which have analysed lumbar spine kinematics in rowers have been carried out on the Concept 2 rowing ergometer. A search of literature was unable to access any spinal kinematic analysis carried out with a rower in a boat on the water. One study analysed the lumbar spine kinematics of a rower on the 'Water Rower' ergometer (WaterRower UK Ltd., London, UK), which is different to the Concept 2 in that it has a flywheel that moves a mass of water rather than air. It is claimed by the manufacturers to be able to maintain constant resistance throughout the stroke to more realistically replicate the on water scenario.

Steer et al., (2006) recruited twelve, novice male rowers who had rowed for a minimum of 1 year and a maximum of 5 years all to take part in the study. All subjects regularly trained on the Concept 2 ergometer. Spinal motion was assessed with the Flock of Birds as described previously with sensors placed at sites as described previously (Bull and McGregor, 2000). Subjects performed a brief warm up on the ergometer and then performed a 300m rowing piece at a fixed stroke rate and heart rate between 130-150bpm. Data were recorded from 50m into the piece until 10m from the end. The subjects then repeated the protocol at a higher rating. The procedure was repeated on two further occasions with a week between recordings. At each session either a Concept 2 or Water

Rower was assigned to the rower in random order so that by the end of the experiment, 2 tests were completed on each ergometer for each subject.

When force profiles were compared for both ergometers there was no difference. When lumbar kinematics were compared, a small number of differences were observed. At low stroke rate, lumbar extension was greater on the Water Rower ($P < 0.05$) although there was no difference in lumbar rotation at the point of peak force between the ergometers. However, at the catch, the pelvis had significantly less anterior rotation on the Water Rower than on the Concept 2 ($P = 0.03$) indicating that the rower was using flexion of the lumbar spine rather than hip flexion to achieve the catch position on the Water Rower. The results of this study indicate that a more optimal position of the lumbar spine is achieved on the Concept 2 compared to the Water Rower; this would have implications for injury. However, a number of factors may have affected these results. The rowers were more familiar with the Concept 2 as they regularly trained on this machine. Also the position of the footplate is different on the Water Rower compared to the Concept 2 which could influence the position of the pelvis at the catch. While this study indicates that the Concept 2 allows a better spine position to be achieved when rowing, more research is required to assess if these findings are replicated in individuals who regularly train on this machine. The Concept 2 is used widely throughout the world, is used for testing international rowers and has a clear, reliable data acquisition system which is likely to keep it as the ergometer of choice for rowers.

To put the findings of the studies into perspective, there are a number of limitations which are common to all studies that should be considered. Firstly, the subject numbers of all studies are modest (mean of 11 participants, range 6-20 participants). However, this reflects the nature of rowing as a minority sport which means that there is limited availability of participants. Furthermore, rowing is a sport which requires a high level of technical skill and standardisation of study participants would have required that those taking part in the studies were of a certain minimum standard, further limiting the study population size. All studies reviewed above stratified participants into well matched cohorts which meant that findings in the studies were less likely to be a reflection of varying technical ability between those completing the study protocols.

The second limitation regards the inherent confines of the equipment which was used to collect kinematic data. MRI may be considered the gold standard method to image the

living spine and associated soft tissues. McGregor et al., (2002) measured spinal kinematics in rowers using Interventional MRI, placing participants into differing positions to mimic rowing technique. While the merit in this study lies in the accuracy of measurement, it adds little to the understanding of lumbar spine injury in rowers as all positions were static postures and provide limited analysis of a dynamic sport. Furthermore, the expense and inconvenience of MRI imaging makes it prohibitive in the study of the wider rowing population, particularly as it can provide no data either on an ergometer or in a boat. Six of the nine studies reviewed above used the 'Flock of Birds' motion analysis system (Bull and McGregor, 2000, McGregor et al., 2005, McGregor et al., 2007, Holt et al., 2003, Mackenzie et al., 2008, Steer et al., 2006). The advantage of this system was that it was able to provide dynamic kinematic data during ergometer rowing. However, it requires a laboratory setting and cannot be used to provide any field data. Although McGregor et al., (2000) calibrated the system against interventional MRI, this was done statically which does not take into account movement of the receiver blocks which may occur over the skin during a dynamic test. All studies involving the Flock of Birds system required fixation of multiple receivers to the body of the participant. The receivers were connected to long cables which, in turn, were connected to the control units; the cables were 'taped over the shoulder of the rower'. Thus the system was cumbersome and it is likely that the equipment would have interfered with the rower's ability to row normally. Although the degree of error noted (due to motion of the receivers on the skin) was $\pm 1^\circ$, the system has a number of inherent errors which increase when the rower moves from the optimal zone of transmitter to receiver separation (between 271 and 723mm); this requires diligence from the operators and increases the complexity of the system. A notable problem is produced by interference of ferrous materials with the system. The Concept 2 ergometer is made of ferrous material (steel) and may have introduced interference and thus inaccuracies in findings. Ng et al., (2009) found that an error (mean of 6.4°) may be introduced due to the interference of the ferrous material of the Concept 2 with the electromagnetic device and thus measurement using this system may not produce valid results. The system requires that the receivers and transmitters are placed more than 150mm away from ferrous materials during data acquisition and this is unlikely to be possible if the receivers are placed on the lower spine of the rower. Surface markers can only give an estimation of joint angles as the location of the joint axis or centre which is being measured is some distance from the marker (Simon, 2004). Also, anatomical variability between subjects means that surface markings may not correlate with location of the desired joint or bony point of interest; when multiple sites are required for

calculation, this will increase inherent error. Thus a high level of skill is required to use this system which may be awkward for the rower, can provide no data out of a laboratory setting and has a number of possible sources of error. The 2 other studies which were reviewed used laboratory based motion capture equipment (Caldwell et al., 2003, and Pollock et al., 2009). The video camera system used by Caldwell et al (2003) is not only affected by factors associated with location and movement of skin surface markers but also by parallax errors associated with filming. Furthermore, the spinal markers were mounted on a projection from the spine which means that the surface marker was located even further from the centre of the joint axis. Data collected by such a method requires digitisation and interpretation which is likely to vary from institution to institution (Simon, 2004). Thus, this is likely to be the study with the greatest source of error. Pollock et al (2009) also used motion tracking but with the use of multiple camera angles which may have enhanced accuracy. However, similar problems regarding parallax error, skin surface marking and post processing correction as that observed in the previous study will have affected the quality of study data obtained using such a method.

The final limitation of the study methods concerns the concept of fatigue. Of the nine studies that were reviewed, seven aimed to examine the effects of fatigue on spinal kinematics. However, none of these studies defined fatigue which is a complex phenomenon and is a result of physiological, neurological and psychological interactions (Marino et al., 2009). Incremental step tests are routinely used to assess the effects the limits of the athlete's physiology as a result of fatigue or, as is now a more popular description, 'volitional exhaustion'. The problem with the use of such a protocol in kinematic analysis is that it introduces another variable within the analysis which is increasing stroke rate. None of the authors have discussed how this may have affected results. This omission means that results should be examined further and concepts other than fatigue may be affecting findings.

Summary of section 1.6.1.

Nine studies were accessed that analysed lumbar spine kinematics in rowers. There were 3 types of study protocol; incremental step tests, 2000 metre tests and 1 hour tests. Seven of the 9 studies were carried out using international rowers as subjects and the other studies used novice and junior rowers. The most popular measurement system was the 'Flock of Birds' (used in 6 studies) which was validated against MRI. Video analysis was used in 1 study and a motion capture system was used in 1. All studies analysed the spine in the

sagittal plane only and all but one used the Concept 2 rowing ergometer. All equipment was subject to some inherent error and none were small and portable enough to allow their use in a field setting. The studies are summarised below in table 1.2.

| Authors | Subjects | Study protocol | Findings |
|---------------------------------|----------------------------------|--|--|
| <i>McGregor et al 2002</i> | 20 male elite rowers | Static Interventional MRI Sagittal plane analysis Static analysis of 4 stroke phases | 1) Rotation of Lsp into flexion at catch 2) Lsp returns to 'neutral' at finish 3) Lsp held 'upright relative to sacrum at catch |
| <i>Bull & McGregor 2000</i> | 6 male elite rowers | Validation of 'Flock of Birds' against MRI 10 mins rowing at max. effort sagittal plane analysis | 1) Fatigue causes increased posterior pelvic tilt throughout stroke, particularly in late drive and finish. |
| <i>McGregor et al 2005</i> | 12 female international rowers | Incremental step test Sagittal plane analysis Flock of Birds | 1) Anterior pelvic tilt at catch 2) Anterior tilt decreases at higher ratings 3) Posterior pelvic tilt at finish 4) Greater Lsp flexion and extension with fatigue 5) Relatively less pelvic rotation with fatigue due to altered lumbopelvic rhythm |
| <i>Caldwell et al 2003</i> | 16 male and female school rowers | 2000 metre test Sagittal plane analysis Video analysis of reflective markers | 1) Fatigue caused lumbar flexion to increase at the catch and mid-drive phase. |
| <i>Pollock et al 2009</i> | 9 female international rowers | 2000 metre test Sagittal plane analysis Motion capture system | 1) Pelvic and lumbar segments move from flexion to extension in 1st phase of stroke 2) Motion of the Lsp is minimal during peak force production 3) Most movement seen at L3-S1. |
| <i>McGregor et al 2007</i> | 7 female international rowers | Incremental step test Sagittal plane analysis Flock of Birds | 1) 2 year training trunk endurance improved lumbo-pelvic ratio allowing equal amounts of lumbar and pelvic rotation |
| <i>Holt et al 2003</i> | 13 male elite rowers | 1 hour rowing piece Sagittal plane analysis Flock of Birds | 1) Significant increase in maximum Lsp flexion and extension with fatigue. 2) Peak force develops significantly later in drive phase with fatigue. |
| <i>Mackenzie et al 2008</i> | 6 male international rowers | 1 hour rowing piece Sagittal plane analysis Flock of Birds | 1) Small increase in Lsp flexion at catch and extension at finish (not significant) 2) Subtle increase in anterior pelvic rotation at catch and posterior pelvic rotation at finish |
| <i>Steer et al 2006</i> | 12 male novice rowers | 300m rowing piece Sagittal plane analysis Flock of Birds | 1) Lsp extension greater on Water Rower 2) Less pelvic anterior rotation at catch on Concept 2 cf Water Rower |

Table 1.2: Summary of spinal kinematics studies in rowers.

Analysis showed a specific pattern of lumbo pelvic motion with anterior rotation observed in the pelvis at the catch position McGregor et al., (2005), Mackenzie et al., (2008) and posterior rotation at the finish position Bull and McGregor, (2000), McGregor et al., (2005), Mackenzie et al., (2008), Pollock et al., (2009). However, McGregor et al., (2002) reported that the lumbar spine rotates into flexion at the catch. Fatigue was associated with a change in spinal kinematics; an increase in posterior pelvic tilt by Bull and McGregor, (2000) and Mackenzie et al., (2008), increase in magnitude of lumbar spine flexion by McGregor et al., (2005), Caldwell et al., (2003), Holt et al., (2003) and Mackenzie et al., (2008) and some studies found an increase in lumbar spine extension, McGregor et al., (2005), Holt et al., (2003) and Mackenzie et al., (2008).

These studies highlight the demands on lumbar spine motion in the rowing stroke, with large ranges of motion noted and alteration of movement patterns as a result of fatigue. They demonstrate that as rowers fatigue, they increase range of movement in their spine and decrease movement in their pelvis as they try to maintain the catch position which is likely to increase loading on the lumbar spine. However, all studies analysed motion in one plane only; the sagittal plane. This is the plane of motion in the lumbar spine which demonstrates the greatest range although most authors did not explain why this plane was chosen. Only one study (Bull and McGregor, 2000) stated that this plane was chosen as it is 'the only plane in which movement takes place'. It is likely that the lumbar spine also moves in both the frontal and transverse planes in rowing as this would reflect normal movement. It is not clear why these planes were not measured in any studies, but may be a reflection of limitations of equipment used to collect data and also that motion in these planes is likely to be small. All of these studies were measured on the Concept 2 ergometer. While rowers spend large amounts of time training on this piece of equipment, there are a number of factors which must be considered when making conclusions from kinematic data collected in this way. Differences between water and ergometer kinematics have received limited attention but were discussed in section 1.1. It is likely that there are differences in spinal kinematics when these two types of rowing are considered and conclusions about boat lumbar spine kinematics should not be inferred from ergometer kinematics. It is also probable that there are likely to be greater movements in the frontal plane of motion in the lumbar spine in a boat; this is expected to be limited on the ergometer. None of the equipment used was portable, which may explain why no measurements were conducted in a boat. There is therefore a need to develop a system

which can provide kinematic analysis of the rower's spine which is light (to allow minimal interference with the ability of the rower to perform), portable (to allow boat measurement), allows more than one plane of motion to be analysed, allows a critical analysis of fatigue and is valid and reliable.

While an understanding of kinematics aids an understanding of why structures fail, knowledge of forces acting on systems is required to build a full picture.

1.6.2 Forces acting on the lumbar spine of rowers.

A search of the literature produced only 1 study that simply estimated the peak compressive and shear forces acting on L5. Morris et al., (2000) noted that rowers frequently present with higher bone mineral density (BMD) in the lumbar spine as a result of loading in this area. Fourteen female rowers and 14 age matched controls had BMD assessed by hologic bone densitometer which demonstrated higher BMD in the lumbar spine of rowers when matched with controls (1069 (0.1) g/cm² vs. 1027 (0.1) g/cm²). The rowers then performed a 6 minute maximal piece on the Concept 2 rowing ergometer and mechanical loading generated in the lumbar spine during this exercise was estimated using a 2 dimensional model of the spine. Reflective markers at various anatomical landmarks were filmed during the rowing piece to allow angle analysis of motion segments. Compressive and shear force were estimated at L4/5 using a two dimensional model of the spine. Shear force was the joint reactive force perpendicular to the spine at the L4/5 joint. Peak compressive and shear forces at this spinal level were calculated as 2730 (609) N and 693 (117) N respectively. Peak compressive force was generated 28-29% of the way through the drive phase of the stroke. Peak compressive forces generated at the lumbar spine were 4.6 times the rowers' body weight. Many factors were estimated in this study, although this level of loading appropriately explains the high BMD seen in rowers' spines. In the absence of any other reference data, this study provides useful information but the limitations of spinal modelling to estimate load should be considered. Specifically, the confines of video motion analysis (discussed in section 1.6.1) and its many sources of error will influence the accuracy of the results of this study. Furthermore, the fact that muscle forces were estimated and the concept of co-contraction was ignored could under-estimate compressive force by as much as 45% and shear force by as much as 70% (Marras and Granata, 1997). Thus, the forces were assessed in a very indirect fashion and only give an indication in this instance. Further work is required to determine accurate values of

compressive and shear forces in rowers' spines which will further explain how such loading ultimately leads to injury.

1.6.3 Muscle activity in the lumbar spine in rowing.

Rehabilitation in low back pain frequently focuses on activity of the muscles of the lumbar spine. Furthermore, many of the studies reviewed above describe changes in the spinal kinematics as a result of fatigue, some of which is in the musculature surrounding the spine. A small number of studies of rowers have analysed muscle activity in an effort to add to knowledge regarding injury in this area.

For sweep rowers, it has been postulated that asymmetries in their spinal muscles may contribute to injury. Parkin et al., (2001) aimed to determine if asymmetry of the strength of the leg and trunk musculature was more prominent in rowers ($N=19$) than in non rowing controls ($N=20$). Ten of the rowers were stroke side oarsmen and 9 were bow side. Muscle strength was determined with an isokinetic dynamometer (Kin -Com). Hamstring and quadriceps strength were assessed by measuring knee flexion and extension. Trunk flexion and extension were assessed in standing with the legs and pelvis restrained. EMG activity of erector spinae muscles at the levels of L2 and L3 were simultaneously recorded while trunk extension strength was measured with the Kin Com. There were no left and right asymmetries in leg strength parameters although knee extensor strength was significantly greater in the rowers. Hamstring: Quadriceps ratio was similar between groups. No differences in trunk strength were observed between groups although analysis of EMG signals were significantly stronger in the rowers in extension and flexion ($P<0.001$) with a trend towards left and right asymmetry in the rowers extension ($P=0.07$). The ANOVA revealed that this asymmetry was related to rowing side ($P<0.01$). These findings were not related to hand dominance.

A surprising finding of this study is that the rowers did not exhibit greater strength in their trunks compared to controls. This could be related to the position of testing which does not replicate trunk activity in the boat. It cannot be concluded that asymmetry is related to injury onset and may be postulated that it is merely an adaptation due to the one sided nature of stroke rowing. Rowing injury studies do not confirm if lumbar spine injuries are more common in sweep rowers than scullers but this study suggests that this should be investigated. This study would have benefitted from the inclusion of a sculling group to clarify this point.

McGregor et al., (2002b) aimed to investigate the trunk strength of elite rowers and the impact of low back pain in order to determine if asymmetries or weaknesses were present. Twenty two, elite, male rowers took part in the study; 13 reported previous low back pain, 5 currently had low back pain and 4 had no history of low back pain. The same protocol was used as previously described by (McGregor et al., 2002); a wooden rowing jig was placed in an MRI scanner and 4 stages of the rowing stroke were analysed for each rower. Both sagittal plane scans and cross sectional images were obtained for the lumbar spine at L4/5 and L5/S1. The muscles that were assessed were the erector spinae, the multifidus and the iliopsoas. There were significant differences with regard to cross sectional area of the muscles when the 3 study groups were analysed. In the multifidus, rowers with both current and previous back pain had significantly larger cross sectional muscle area compared to those who never had low back pain ($P < 0.0001$). Differences were also seen in the erector spinae. At the L4/5 level, subjects with both a current and previous history of lower back pain had significantly larger muscles than those who had never had back pain ($P < 0.001$). However, at the L5/S1 level, the differences were reversed when the subjects who had never had back pain had larger erector spinae cross sectional area than those with a previous history of pain ($P < 0.05$). When the ratio of total back extensor muscle (multifidus + erector spinae) was compared, subjects with a previous history of back pain had a significantly lower ratio than those with no history of low back pain ($P < 0.05$). No significant left and right asymmetries were observed.

The aim of this study was to investigate trunk muscle *strength* and while cross sectional area may give an indication of ability to generate force, it may not give an accurate measure of strength. It may be more important to measure endurance rather than strength in rowers' spines due to the nature of the sport. Inclusion of data regarding changes in muscle cross sectional area at different stages of the rowing stroke may have added to knowledge of lumbar kinematics measured in the previous study to provide a more comprehensive picture. The authors concluded that low back pain in elite oarsmen does not appear to be the result of weakness or asymmetry of the multifidus or erector spinae muscle group.

MRI is limited by the fact that it can give little information regarding real time activity of spinal muscles in rowers. While EMG cannot provide specific information regarding muscle strength, it can provide detail of muscle activity. In a study which was previously

described above, Caldwell et al., (2003) measured spinal kinematics of 16 rowers as well as collecting data (with surface EMG) which examined magnitude of activity of 3 erector spinae muscles during a fatiguing rowing trial on the ergometer (2000m test). EMG electrodes were placed at the level of the L4/5 interspinous space, 2cm lateral to the midline; this site was identified by the authors as the multifidus. Electrodes were also placed at the lateral border of the 12th rib at the level of L2 (iliocostalis muscle) and 3cm lateral to the spinous process of L1 (longissimus). Activity was recorded during the drive phase of the stroke. The pattern of muscle activity recorded during the drive phase of the rowing stroke was similar for all the muscles and showed an increase in activity to maximal values during the middle of the drive phase. Muscle activity increased significantly as the rowing trial progressed from levels of 50% maximum voluntary contraction (MVC) to 80% MVC. The authors compared this to levels of 35% and 40% MVC of multifidus when lifting a heavy box weighing 250N. Thus the authors concluded that muscle activity by the end of the rowing test was very high.

While the results of this study suggest that fatigue of the spinal extensors may be apparent, the findings indicate high level of activity. Clarification of fatigue would be provided if an additional physiological parameter such as blood lactate levels were measured; this would make the results more conclusive. This study did not study activity of trunk flexors which would have provided a much more comprehensive picture. As with previous studies, measurement in only one plane on an ergometer may not replicate boat rowing. However, the findings of this study indicate that rowers demonstrate very high activity of lumbar muscles during rowing which increases significantly as the activity continues. This suggests that more work examining the effects on fatigue on spinal kinematics is merited.

Pollock et al., (2009) analysed EMG activity of trunk muscles at the same time as spinal kinematics (described above). Nine international female rowers performed a 2000m race simulation on a Concept 2 ergometer. EMG electrodes were placed over trunk flexors and extensors at various sites as well as latissimus dorsi, hip extensors, biceps femoris and gluteus maximus. EMG data were collected for 30 seconds starting at 250m and at 250m increments following on. Only the first 250m collection period was analysed. Five strokes were analysed for the purposes of this study. Two specific areas of the drive phase were discussed by the authors; the period of peak force production and the phase of the stroke at which co-activation between the flexor and extensor muscle groups were identified on

EMG. The period of peak force production was defined as 14-24% post catch defined by force on the handle of the ergometer.

Analysis of results showed that the extensors of the pelvis and the spine were initiated within the first 6% of the drive phase shortly after the catch. This is seen as the pelvic and lumbar segments quickly move from positions of flexion into extension. The peak EMG amplitudes of the extensor muscles of the pelvis, lumbar and mid – lower thoracic spine were observed during the period of peak force production (14-24%, post catch). The latissimus dorsi reached its peak amplitude right at the end of this time period at 23.1% (6.4) of the stroke cycle. During the period of peak force production there were minimal amounts of co-activation among the flexors and extensors of the trunk, demonstrating that there was very little trunk flexor activity during the drive phase. While the extensors represented 60% of muscle activity during the period of peak force production, the flexors only represented 6%. The authors found that the period of co-activation was found in the mid to late drive phase for all subjects. The period of co-activation is defined as the EMG activity between the onset of the first flexor muscle and the end of the last extensor muscle. The mean period of co-activation was from 28.2% (2.2) to 36.8% (3.2) following the catch. The end of the drive phase was assessed to be at 44.3% (1.2) of the stroke. The peak period of flexor muscle activity however was found to be at 40% of the stroke which is right at the end of the drive phase and the mean time for onset of flexor muscle group activity was at 29% of the stroke cycle.

The authors suggest that co-ordination of the extensors of the spine and pelvis after the catch are an effective strategy to support the spine as forces increase with the initiation of the drive phase up to the period of peak force production. The kinematics which are associated with the period of peak extensor activity demonstrated that the spine was kept relatively fixed which appears to be an effective motor control strategy. The pattern of recruitment of trunk flexors demonstrates that the primary role of the abdominal muscles is to slow extension of the trunk as the centre of mass is brought further into extension at the finish position. The limited activity of the extensors at the end of the drive phase, allows the flexors to flex the trunk at the initiation of the recovery. The fact that low levels of abdominal muscle activation (flexors) were observed at the period of peak force production seems to 'negate the commonly held belief that the abdominal muscles are important in spine stabilisation' (Pollock et al., 2009). The authors also suggest that increased co-

activation of the flexors and extensors would also result in increased compressive spinal forces and may contribute to injury.

Of the 9 subjects in this study, 3 had reported history of low back pain, but this was not discussed further and there was no separate analysis of their data. This may have provided some limited information regarding contributing factors or consequences of such an injury. As with all previous studies, findings on the ergometer may not translate to activity in the boat. It is likely that the instability of the boat on the water and the rotational patterns of sweep rowing would provide different EMG findings. Surface EMG has many limitations, one of which is that it gives information only regarding activity and provides no data regarding strength of contraction, endurance of muscle and may be subject to cross talk from other muscle groups. The study examined 5 strokes taken at the beginning of the test which means that the data is likely to provide little information regarding muscle recruitment patterns when the subject is fatigued. However, some important findings warrant further research in this area. The dominance of extensor muscle activity of the spine has important implications for rehabilitation of rowers with lumbar spine injury. Modern rehabilitation of low back pain has placed particular emphasis on co-contraction of the trunk muscles, particularly using protocols such as Pilates type exercise. The findings of this study suggest that during peak force generation, such co-contraction does not exist and the extensor muscles dominate. Thus rowers may be using inappropriate rehabilitation protocols. Further, traditional 'core stability' programmes, with their emphasis on co-contraction are included in most rowers' training now; this study suggests that more emphasis should be placed on training the spinal extensors as well as training eccentric action of the flexors.

Summary of section 1.6.3.

Information regarding muscle activity in the lumbar spine of rowers is limited. Of the 4 studies that were accessed, only 1 measured strength as well as EMG activity (Parkin et al., 2001). However, while Parkin et al found that there was no difference in trunk strength between rowers and controls, rowers exhibited higher EMG activity in their trunk extensors. This may suggest that EMG activity correlates poorly with strength. Both Caldwell et al., (2003) and Pollock et al., (2009) analysed EMG activity of the trunk muscles during a 2000m rowing trial. Caldwell et al., (2003) found that activity of the spinal extensor muscles were high and increased as the test continued while Pollock et al., (2009) found that spinal extensor muscle activity dominated the rowing stroke. However,

while both studies reflect trunk muscle activity, they present no information regarding strength or endurance of muscle which support the lumbar spine. McGregor et al., (2002b) analysed cross sectional area of muscles at 2 levels of the lumbar spine which demonstrated differences between groups of rowers who had no history or present/previous history of back pain, although this study provided no information regarding muscle strength or endurance. Thus, the limited data available provides limited information regarding endurance of the trunk muscles in rowers. There is a specific need to investigate spinal muscle endurance to examine how this contributes to or helps prevent lumbar spine injury.

1.7 Summary and discussion of preceding sections.

The preceding review of literature has highlighted a number of issues that require further clarification. There are also some omissions in detail which requires additional research to build a better understanding of the issue of lower back injury in rowers. Consideration of these issues will form the basis of the objectives of the following studies.

1) While there have been a small number of studies examining injury in rowers, none demonstrated best practice in injury surveillance. However, a consistent finding in all studies was that lumbar spine injury is common and is a problem in rowers. Krosshaug and Verhagen (2010) state that ‘the strongest design for an aetiological study is a prospective cohort study’. Thus there is a need for a study of this design in rowers. The problem of low back pain in rowers needs to be put into context by obtaining data which can be compared to the findings in the general population. Methodological limitations in most studies meant that predictors for injury were not generally measured. Thus the first objective of this thesis is: *To establish an injury profile and identify predictors for injury in rowers.*

2) Examination of spinal kinematics has been carried out in a number of good quality studies. This work has helped identify the motion demands that rowing places on the lumbar spine. All studies took place on rowing ergometers and none examined spinal kinematics in a boat. There is thus a need to examine spinal kinematics in a boat and to compare them to those on an ergometer. All the studies that were reviewed measured spinal motion in the sagittal plane only. While this is the plane in which most movement takes place, Nolte (2005) noted that rowers also move in the frontal plane in the boat. Nolte suggested that rowers shift their lower back in the frontal plane to regain balance of a boat which can ‘lead to extended loads in their lower back which may increase injury risk’. It would seem likely that the existence of this movement would be a clear difference between the boat and ergometer as the ergometer is on a stable surface and the boat is on an unstable surface with most movement from side to side (in the frontal plane). As no other study has examined frontal plane motion, examination of lumbar spine kinematics in both the boat and the ergometer in this plane, may provide a better understanding of the causes of lumbar spine injury. Thus the second objective of this study is to: *Determine the frontal plane kinematics of lumbar spine when rowing* and the third objective of this study is to:

Compare the frontal plane kinematics of lumbar spine when rowing in a boat with rowing on an ergometer. The fourth objective is to: Compare the sagittal plane kinematics of lumbar spine when rowing in a boat with rowing on an ergometer.

3) A consistent finding of all studies which examined spinal kinematics on the ergometer in a dynamic fashion was that as rowers fatigued, spinal kinematics altered. As the rowers are already loading a flexed lumbar spine from the outset, this has implications for injury. To provide a more comprehensive picture, there is a need for a study which examines spinal kinematics under conditions of fatigue in both the frontal and sagittal plane. Therefore the fifth objective is to: *Examine the kinematics of the lumbar spine in both the frontal and sagittal plane under the conditions of fatigue.* As all previous studies have only examined the effect of fatigue on lumbar spine kinematics on an ergometer, there is a need to examine if the same effect is seen in a boat which may help explain why the ergometer may increase risk of injury. The final objective is to: *Compare the kinematics of lumbar spine when rowing in a boat with rowing on an ergometer, under the conditions of fatigue.*

1.7.1 STUDY HYPOTHESIS

The preceding review of literature has led to the hypothesis that:

The risk of sustaining a lumbar spine injury in rowing is significant and is influenced by rowing mode (ergometer or boat) and fatigue.

1.7.2 STUDY AIM

To determine if lumbar spine injury is a significant problem in rowers and to examine how kinematics of the lumbar spine, rowing mode and fatigue relate to this injury.

1.7.3 STUDY OBJECTIVES

The objectives outlined in section 1.7.1 above are summarised below:

- Establish an injury profile and identify predictors for injury in rowers.
- Determine the frontal plane kinematics of the lumbar spine when rowing.

- Compare the frontal plane kinematics of the lumbar spine when rowing in a boat with rowing on an ergometer.
- Compare the sagittal plane kinematics of the lumbar spine when rowing in a boat with rowing on an ergometer.
- Examine kinematics of lumbar spine in both the frontal and sagittal plane under the conditions of fatigue.
- Compare the kinematics of the lumbar spine when rowing in a boat with rowing on an ergometer, under the conditions of fatigue.

The following flow chart (figure 1.10) outlines the stages of the studies that will follow.

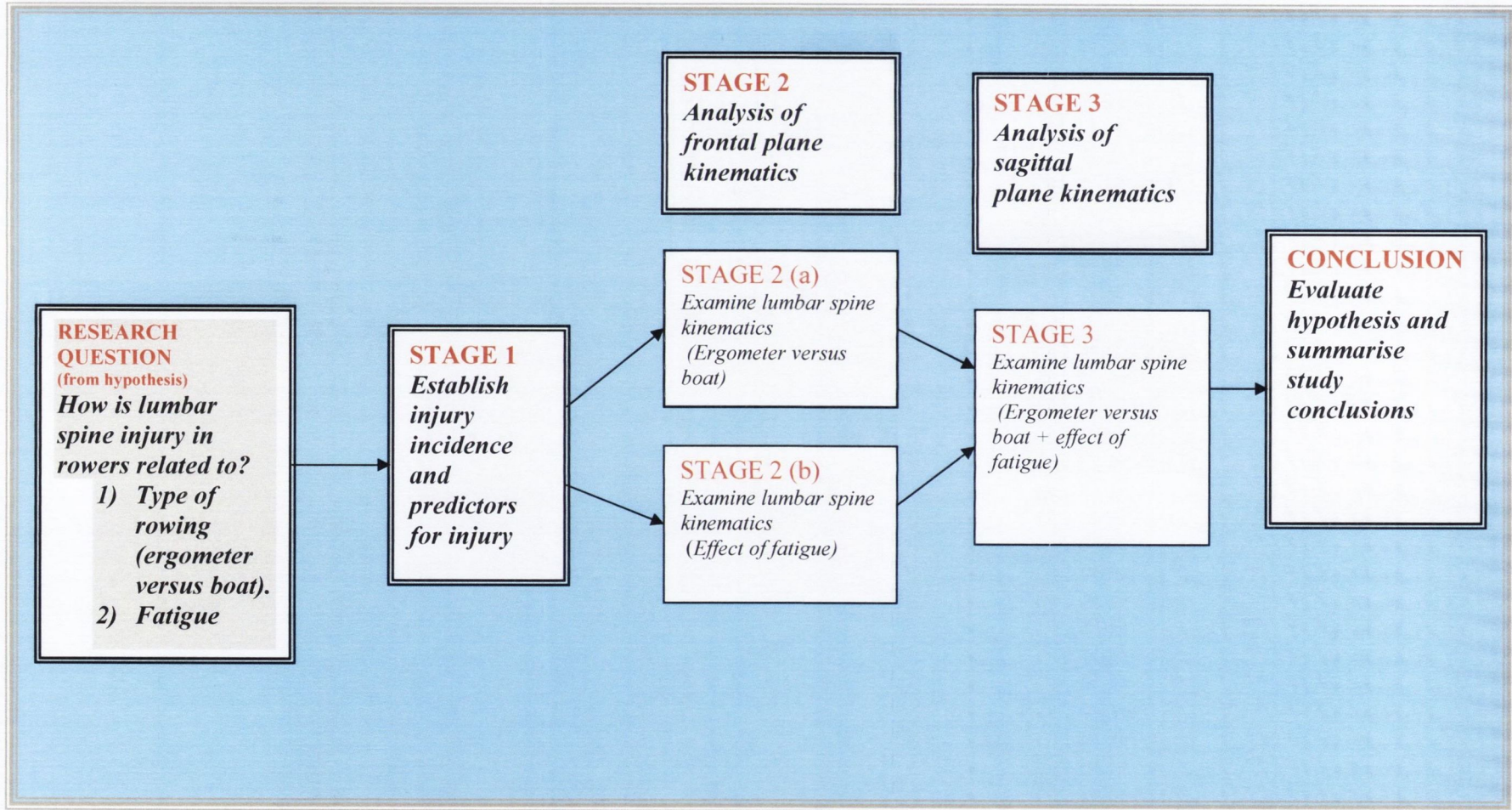


Figure 1.10: Flow chart to represent the stages of the studies of the thesis.

CHAPTER 2

STUDY 1

A 12 MONTH PROSPECTIVE COHORT STUDY OF INJURY IN INTERNATIONAL ROWERS.

2.1 ABSTRACT.

Objective: To describe injury incidence, and association with type and volume of training in international rowers.

Methods: Twenty international rowers who were competing as part of the Irish Amateur Rowing Union squad system were recruited for this study. A prospective cohort design was used over a 12 month period. The rowers were interviewed monthly and data was collected regarding their training and competition exposure as well as their injury experience.

Results: A mean injury rate of 3.67 per 1000 exposure hours was reported with a total of 44 injuries reported in a 12 month period. The mean number of injuries sustained per athlete was 2.2 (1.24) over the 12 month period. The area where the greatest number of injuries were reported was the lumbar spine (31.8% of total injuries, 95% CI, 20 to 50%) followed by the knee (15.9% of total injuries, 95% CI, 10 to 30%) and the cervical spine (11.4% of total injuries, 95% CI, 5 to 24%). Sixty five percent of the study cohort sustained an injury to the lumbar spine over the 12 month study period. Half of the injuries (22 injuries, 50% of total reported injuries) were to the spine. ($\chi^2 = 30.8$, $df = 9$, $P=0.0003$). Ergometer training load was the most significantly associated with injury risk ($r = 0.68$, $P=0.01$).

Conclusion: International rowers are at higher risk of injury than most non-contact sports and some contact sports. The high risk of lumbar spine injury and the significant association of high volume of ergometer training merit further research to reduce training and competition time lost to injury.

2.2 INTRODUCTION.

Section 1.3.2 of this thesis reviewed the literature which examined the incidence and profile of injuries associated with rowing and rowing training. An extensive search of the literature revealed studies that either comprised a retrospective review of medical notes (Reid et al., (1989), Coburn and Wajswelner, (1993), Hickey et al., (1997), Edgar, (1993)) or retrospective questionnaires (Budgett and Fuller, (1989), Boland and Hosea, (1991), Smoljanovic et al., (2009)) which did not provide standardised injury incidence per 1000 hours, or fully describe factors which may predict injury. Only one study (Parkkari et al., 2004) prospectively examined injury incidence associated with active living in the general population; the results of which gave no more than injury incidence at 1.5 /1000 hours. Despite this, the studies were consistent in quoting lumbar spine injury to be the most common injury sustained in rowers, suggesting that further investigation is required in this area.

Section 1.3.1 defined best practice in sport injury surveillance and Van Mechelen, (1997a) stated that the first stage in examination of any sports injury is to ‘establish the extent of the injury problem including incidence and severity’. While the studies cited above indicate that injury is a part of rowing, none conform to best practice as outlined in section 1.3.1. While previous studies have suggested that lumbar spine injury is a problem, there is a need to confirm this in the context of other injuries first. Fuller et al., (2006) stated that match and training exposure should be combined with a prospective cohort study to ‘enable relations between the incidence of injury and risk factors in the study population to be explored’. Thus, to begin to examine injury in rowers, there is a need for a prospective cohort study to establish an injury profile (establish the extent of the problem) and to identify factors which may predict injury in rowers.

2.3 AIMS AND OBJECTIVES.

Aims

The first aim of this study was to carry out a 12 month prospective survey of injury in international rowers, to establish an injury profile for the sport. The second aim was to identify the predictors of injury.

Objectives

- To establish injury incidence in rowers.
- To establish injury severity in rowers.
- To establish racing and training exposure.
- To classify injuries by location, type and mechanism (traumatic or overuse).
- To investigate predictors for injury by investigating the relationship between training and racing (method and exposure time) and injury onset.

2.4 METHODS

2.4.1 Study design

The study design was a prospective cohort study carried out over a 12 month period on international rowers who were competing as part of the Irish Amateur Rowing Union squad system. The study period was October 2003 to October 2004. Data was recorded monthly, by telephone interview. Ethical permission was passed internally by Trinity College School of Physiotherapy, written informed consent was obtained from the Irish Amateur Rowing Union and the athletes involved.

2.4.2 Participants

The subject group examined in this study were senior male and female international rowers. All were training and competing as part of the Irish Team and were confirmed by the head coach to be potential athletes to compete at the 2004 Olympic Games, World Senior or Under 23 World Championships. The head coach provided a list and contact details of all athletes with such potential for the 2003/2004 season. All athletes on the list were invited by email to be part of the study by the chief investigator. To be eligible for the study, all athletes had to be over 18 years of age and had to have gained international selection within the previous 2 years. Participants in the study were provided with full details of the study and signed a consent form confirming enrolment in the study and acknowledged the confidentiality of their personal details.

2.4.3 Measurement questionnaire and procedure

The chief investigator called each athlete once a month for 12 months. The telephone interview was structured and consisted of mostly closed ended questions which gathered

details regarding hours and type of training and racing as well as injury experience. The chief investigator was a chartered physiotherapist who interpreted injury reports to give a working diagnosis in cases where the athlete had not been seen by a physiotherapy or medical professional.

The monthly questionnaire was adapted from the Rugby Injury and Performance Project (RIPP), (Waller et al., 1994). Adaptations to the RIPP questionnaire design were required to improve its suitability for its use on a rowing cohort. The RIPP collected data on a weekly basis by telephone; however, this was not possible due to financial and practical constraints of this project and data was therefore collected monthly data by one investigator. The words 'practice' and 'game' in the RIPP format were changed to 'training' and 'racing'. In the RIPP injury report form, the data requesting information regarding 'foul play' was removed from the rowing format. The monthly interview was changed from the RIPP to include training details which were appropriate to rowing. Specifically these were: Boat; Ergometer; Heavy weights; Endurance weights and Land (other). Training was further broken down to investigate fitness components which were: Strength; Endurance; Interval; Flexibility; Core stability. Questions regarding psychological state, alcohol use and protective equipment were removed from the RIPP and a question was included regarding weight control for the lightweight rowers.

All athletes completed a baseline questionnaire to establish details such as date of birth, occupation and international rowing experience as well as injury details for the previous 12 months (Appendix A). The monthly questionnaire (Appendix B) comprised 3 sections, the first of which examined details of the volume and type of training that the athlete took part in during the previous month. Details were also collected regarding warm up and warm down procedures, and also any training or racing that was missed because of injury or illness. The second section noted if the athlete had experienced injuries over the previous month. If an injury was sustained, it was established if it was a result of rowing or rowing training. If it was as a result of rowing or rowing training, details were documented in section 3. Section 3 examined detailed aspects of the injury including site, mode of onset and treatment received. It was also established if the athlete had previously injured this area.

2.4.4 Injury definition.

For the purposes of this project an injury was defined as a problem, which caused the athlete to miss:

- At least one competition (regatta, head race or trial) OR
- At least 2 training sessions OR
- Required at least one visit to a health professional for treatment.

This definition was adapted from the RIPP, (Waller et al., 1994) by changing the word 'game' to 'competition'.

2.4.5 Statistical analysis.

Results were entered into a Microsoft Excel (2003) spreadsheet and analysed by calculating percentages and injury incidence per 1000 hours. All computations involving a 95% Confidence interval were calculated using the Confidence Interval Analysis Package (Altman et al., 2000). Further analysis involved the use of chi-squared, Pearson's correlation and linear regression analysis which were computed using SPSS v15. Alpha level was set at $P < 0.05$.

2.5 RESULTS

Of the 26 athletes who were contacted, 20 agreed to participate. All 20 supplied training and injury details throughout the study, although one athlete was unable to return to full training and racing following illness. Of the cohort, 12 were male and 8 were female with a mean age of 26.3 (4.2) years and a mean number of years of rowing experience of 10.9 (3.8) years. Fifteen of the team described themselves as lightweight rowers and five as heavyweight rowers, although the lightweights would generally only be 'on weight' at specific times of the season (see section 1.1.6). All rowers were training full time as the data was collected during the Olympic Games year.

2.5.1 Injury in the previous 12 months (retrospective baseline data).

Ten of the cohort had missed training in the previous season as a result of injury; the mean time loss was 4.6 (6.6) weeks (range 1-24 weeks). Sixteen participants reported injury in the previous 12 months and a total of 34 injuries were noted. Five participants reported 1

injury, 5 reported 2 injuries, 5 reported 3 injuries and 1 reported a total of 4 injuries in the previous 12 months. The most commonly reported injury was to the lumbar spine (29% of total), followed by the wrist and forearm (20.5% of total). Other injuries were reported at the shoulder (4 injuries), hip (3 injuries), upper back (3 injuries), ankle (2 injuries) and 1 injury each reported in the rib and the elbow region.

2.5.2 Incidence of injury

A mean injury incidence of 3.67 per 1000 hours (training and competing) was reported with a total of 44 injuries reported in a 12 month period. A total of 12,905.3 (mean 645.3 (167.1)) hours were spent training and a total of 61.5 (mean 3.1(1.1)) hours were spent competing. The total time spent training and racing was 12,956.8 hours for the 12 month period and the mean time for individuals was 647.8 hours (167.5). The mean number of injuries sustained per athlete was 2.2 (1.2) over the 12 month period. The month when the greatest number of injuries were sustained was November (14 injuries reported) and the lowest number of injuries were in July and August when no injuries were reported (see Figure 2.1).

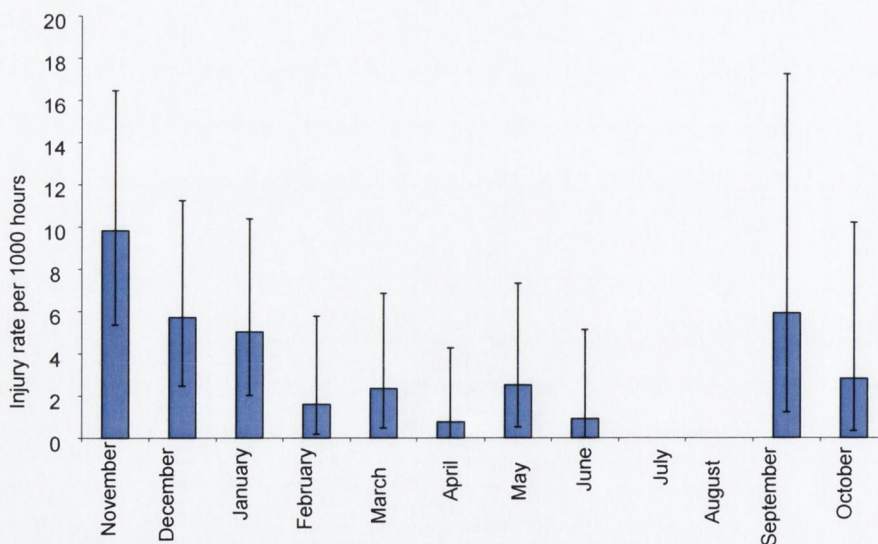


Figure 2.1 Injury counts per month (with 95% CI).

2.5.3 Subcategories of injury.

Only one athlete missed any racing as a result of injury (lumbar disc injury). All but one athlete (Achilles tendinitis) visited a health professional and this athlete's injury fell under the subcategory of 'missed at least 2 training sessions'. Thus 42 injuries were defined under the subcategory of requiring a visit to a health professional.

2.5.4 Injury reporting

Two athletes did not see either a chartered physiotherapist who was part of the IARU system, or a medical doctor. One athlete attended a chiropractor and was diagnosed with SIJ dysfunction and one did not seek treatment but reported Achilles tendinitis, a condition for which he had been previously treated by a chartered physiotherapist. In these 2 instances the chief investigator confirmed the diagnosis. All other injuries (42) were diagnosed by chartered physiotherapists or medical doctors.

2.5.5 Individual injury rates.

The individual injury rates including the representation of acute versus chronic or recurring injuries are reported in table 2.1. All injuries were newly reported so those marked as chronic or recurring had been sustained by the athlete before. No injuries carried over from one month to another. There were 3 reports of the same injury returning in the 12 month period; 2 cervical spine injuries and 1 thoracic spine injury.

| SUBJECT | Training hours | Racing hours | Total training+racing hrs | no. injuries | (acute) | (chronic) | INJ/1000 HRS | 95% CI for injury rate |
|-----------------|----------------|--------------|---------------------------|--------------|-------------|------------|--------------|------------------------|
| 1 | 957.3 | 4.9 | 962.2 | 1.0 | 1.0 | 0.0 | 1.0 | 0-5.8 |
| 2 | 509.0 | 2.8 | 511.8 | 4.0 | 4.0 | 0.0 | 7.8 | 2.1-20 |
| 3 | 491.0 | 4.0 | 495.0 | 2.0 | 2.0 | 0.0 | 4.0 | 0.5-14.6 |
| 4 | 704.8 | 4.4 | 709.2 | 3.0 | 2.0 | 1.0 | 4.2 | 0.0-12.4 |
| 5 | 547.4 | 3.5 | 550.9 | 1.0 | 1.0 | 0.0 | 1.8 | 0-10.1 |
| 6 | 726.3 | 4.9 | 731.2 | 2.0 | 1.0 | 1.0 | 2.7 | 0.3-9.9 |
| 7 | 916.5 | 2.2 | 918.7 | 3.0 | 3.0 | 0.0 | 3.3 | 0.7-9.5 |
| 8 | 697.7 | 3.0 | 700.7 | 3.0 | 2.0 | 1.0 | 4.3 | 0.0-12.5 |
| 9 | 663.9 | 4.7 | 668.6 | 2.0 | 2.0 | 0.0 | 3.0 | 0.4-10.8 |
| 10 | 616.0 | 2.5 | 608.5 | 2.0 | 0.0 | 2.0 | 3.3 | 0.4-11.7 |
| 11 | 503.4 | 2.7 | 506.1 | 0.0 | 0.0 | 0.0 | 0.0 | -- |
| 12 | 436.0 | 0.9 | 436.9 | 3.0 | 3.0 | 0.0 | 6.9 | 1.4-20.1 |
| 13 | 585.1 | 2.8 | 587.9 | 1.0 | 1.0 | 0.0 | 1.7 | 0-9.5 |
| 14 | 1011.5 | 3.8 | 1015.3 | 2.0 | 2.0 | 0.0 | 2.0 | 0.2-9.7 |
| 15 | 503.4 | 3.2 | 506.6 | 4.0 | 3.0 | 1.0 | 7.9 | 2.2-20.2 |
| 16 | 597.6 | 3.1 | 600.7 | 4.0 | 3.0 | 1.0 | 6.7 | 1.8-17 |
| 17 | 424.8 | 2.3 | 427.1 | 3.0 | 3.0 | 0.0 | 7.0 | 1.4-20.5 |
| 18 | 583.3 | 2.5 | 585.8 | 0.0 | 0.0 | 0.0 | 0.0 | -- |
| 19 | 774.4 | 1.0 | 775.4 | 1.0 | 1.0 | 0.0 | 1.3 | 0-7.2 |
| 20 | 655.9 | 2.3 | 658.2 | 3.0 | 1.0 | 2.0 | 4.6 | 0.0-13.3 |
| TOTAL | 12905.3 | 61.5 | 12956.8 | 44.0 | 35.0 | 9.0 | | |
| MEAN | 645.3 | 3.1 | 647.8 | 2.2 | | | 3.7 | |
| St. dev. | 167.1 | 1.1 | 167.5 | 1.2 | | | 2.5 | |

Table 2.1: Training, racing and injury rate profiles for each subject including the number of acute versus chronic or recurring injuries.

2.5.6 Site of injury

The most commonly reported injury in this study was to the *lumbar spine* which was reported by 65% of the cohort. Lumbar spine injury constituted 31.82% of total reported injuries, (95% CI, 20 to 50%) followed by the knee (15.91% of total injuries, 95% CI, 10 to 30%) and the cervical spine (11.36% of total injuries, 95% CI, 5 to 24%) (Figure 2.2). Half of the injuries (22 injuries, 50% of total reported injuries) were to the spine. ($\chi^2 = 30.8$, $df = 19$, $P=0.0003$). Sixty five percent of the cohort reported an injury to the lumbar spine. Individual injury counts for each area are shown in table 2.2.

| Injury area | no. injuries | % of total | 95% CI |
|-------------------------|--------------|------------|---------|
| <i>Lumbar spine</i> | 14 | 31.8 | 20 - 50 |
| <i>Knee</i> | 7 | 15.9 | 10 - 30 |
| <i>Cervical spine</i> | 5 | 11.4 | 5 - 24 |
| <i>Wrist</i> | 4 | 9.1 | 4 - 21 |
| <i>Sacroiliac joint</i> | 3 | 6.8 | 2 - 18 |
| <i>Thoracic spine</i> | 3 | 6.8 | 2 - 18 |
| <i>Thigh</i> | 2 | 4.6 | 1 - 15 |
| <i>Shoulder</i> | 2 | 4.6 | 1 - 15 |
| <i>Ankle</i> | 2 | 4.6 | 1 - 15 |
| <i>Calf</i> | 1 | 2.3 | 0 - 11 |
| <i>Foot</i> | 1 | 2.3 | 0 - 11 |
| Total | 44 | | |

Table 2.2: Individual injury counts for each area.

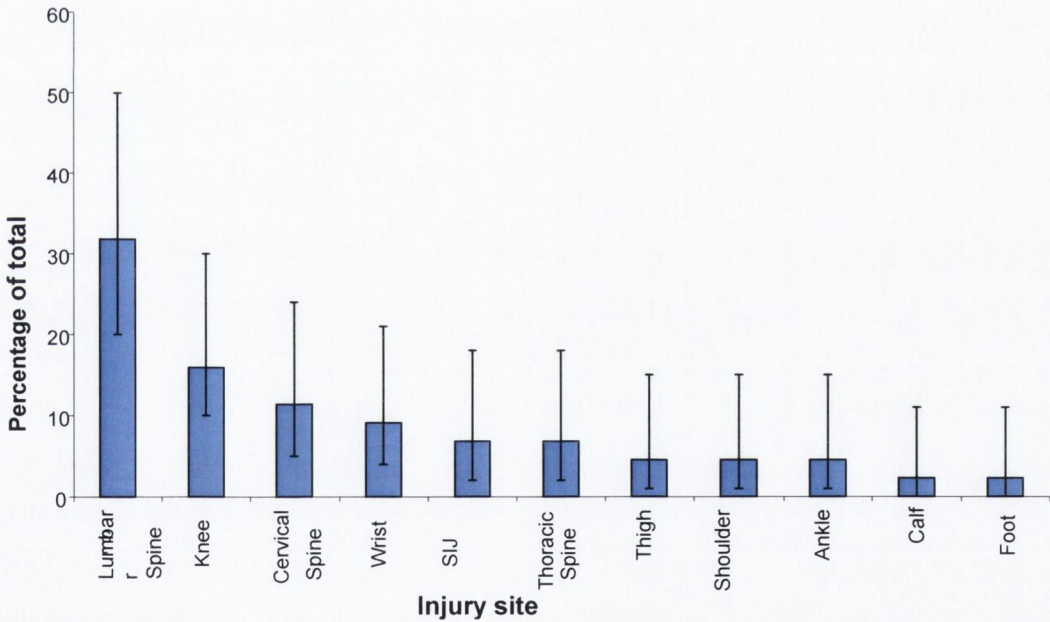


Figure 2.2 Sites of injuries as a percentage of total reported injuries (with 95% CI).

2.5.7 Type of injury

The type of injury experienced by the rowers are shown in table 2.3, there were significant differences between the numbers in each category ($\chi^2 = 53$, $df = 19$, $P < 0.0001$). 'Spinal

facet joint' injuries were the most commonly reported injury at 31.8% of the total injuries followed by 'tendonitis' (27.3%) and lumbar disc and muscle strain at 11.4%.

| Injury type | number of injuries | % of total | 95% CI |
|-------------------------------------|--------------------------|------------|-------------|
| <i>Facet joint injury</i> | 14 | 31.8 | 20 - 46 |
| <i>Tendinitis</i> | 12 | 27.3 | 16.8 - 41.3 |
| <i>Sacroiliac joint dysfunction</i> | 3 | 6.8 | 2.3 - 18.2 |
| <i>Lumbar disc</i> | 5 | 11.4 | 5 - 24 |
| <i>Muscle strain</i> | 5 | 11.4 | 5 - 24 |
| <i>Joint impingement</i> | 1 | 2.3 | 0.4 - 11.8 |
| <i>Compartment syndrome</i> | 1 | 2.3 | 0.4 - 11.8 |
| <i>Contusion</i> | 1 | 2.3 | 0.4 - 11.8 |
| <i>Fracture</i> | 1 | 2.3 | 0.4 - 11.8 |
| <i>Patellofemoral syndrome</i> | 1 | 2.3 | 0.4 - 11.8 |
| Total | 44 | | |

Table 2.3: Types of injuries.

'Facet joint injury' was reported of spinal joints by chartered physiotherapists on all occasions. Of the injuries that were reported as 'tendinitis', 3 were of the wrist (not specifically reported as tenosynovitis or intersection syndrome), 6 were at the knee (1 patella tendon, 1 iliotibial band, 2 biceps femoris, 2 pes anserinus, 1 tibialis posterior and 2 Achilles tendon. Of those reported as muscle strain, 2 were of hamstrings, 1 quadriceps and 2 of lumbar spine musculature. Compartment syndrome of the forearm was reported as an acute injury which did not require surgery. Contusion was reported of the lower back following a boat crash and fracture was reported at the first metatarsal. Patellofemoral joint syndrome was diagnosed by a chartered physiotherapist when an athlete presented with anterior knee pain.

2.5.8 Relationship between number of injuries and training volume.

The monthly injury rates and training volumes are shown in table 2.5. There was a non-significant correlation between monthly total training time and injury, and between mean training time and injury (both $r = 0.543$, $P=0.068$). When examining the specific training

type volumes, there were significant associations between monthly ergometer time and injury ($r = 0.75$, $P=0.01$), time spent training with heavy weights and injury ($r = 0.66$, $P=0.02$), time spent on core stability and injury ($r = 0.68$, $P=0.01$). There were also non significant correlations for time spent on flexibility and injury ($r = 0.53$, $P = 0.08$), time training in a boat and injury($r = -0.01$, $P=1.0$) and time spent on light-weights and injury ($r = 0.09$, $P=0.77$). The correlations with injury could thus be summarised as the following according to Cohen and Holliday (1982) in table 2.4:

| Training type | Correlation coefficient (r) | Strength of correlation |
|----------------------|------------------------------------|--------------------------------|
| Ergometer | 0.75 | <i>High</i> |
| Core stability | 0.68 | <i>Modest</i> |
| Heavy weights | 0.66 | <i>Modest</i> |
| Flexibility | 0.53 | <i>Modest</i> |
| Light weights | 0.09 | <i>Very low</i> |
| Boat | 0.01 | <i>Very low</i> |

Table 2.4: Summary of correlation between training types and injury.

Each of the significant correlations was further analysed by a backwards multiple regression model. Each progressive model was significant and it was determined that time on heavy weights accounted for 3.4% of the variation in the number of injuries, while core stability time accounted for 0.5% of the variation and ergometer time 51.2%.

| Month | Number of injuries | mean training hours | total training hours | Injury rate per 1000 hours with 95% CI | |
|-------|--------------------|---------------------|----------------------|--|------------|
| Nov | 14 | 71.3 | 1426.8 | 9.81 | 5.4 - 16.5 |
| Dec | 8 | 70.1 | 1402.8 | 5.70 | 2.5 - 11.2 |
| Jan | 7 | 69.5 | 1390.8 | 5.03 | 2 - 10.4 |
| Feb | 2 | 62.6 | 1252 | 1.60 | 0.2 - 5.7 |
| Mar | 3 | 64.1 | 1282.4 | 2.34 | 0.5 - 6.8 |
| Apr | 1 | 65.1 | 1302.4 | 0.77 | 0.1 - 4.3 |
| May | 3 | 54.3 | 1085 | 2.51 | 0.6 - 8.1 |
| June | 1 | 54.3 | 1085.6 | 0.92 | 2.3 - 5.1 |
| July | 0 | 52.3 | 1046.4 | 0.00 | |
| Aug | 0 | 23.5 | 469.4 | 0.00 | |
| Sept | 3 | 25.4 | 508.8 | 5.90 | 1.2 - 17.3 |
| Oct | 2 | 35.4 | 708.4 | 2.82 | 0.4 - 10.2 |

Table 2.5: Relationship between number of injuries and training volume.

Table 2.6 represents the relationship between the type and volume of training and the injury count for individual months. The type of training is shown as the mean number of sessions of each activity completed on a weekly basis for that month by the full cohort.

| Month | Boat sessions/ week | Ergometer sessions/ week | Heavy weights sessions/ week | Light weights sessions/ week | Core stability sessions/ week | Flexibility Sessions/ week | Number of injuries |
|-----------|---------------------|--------------------------|------------------------------|------------------------------|-------------------------------|----------------------------|--------------------|
| November | 6.7 | 2.8 | 2.1 | 0.7 | 3.7 | 4.9 | 14 |
| December | 7.9 | 2.3 | 2.3 | 0.5 | 3 | 4.5 | 8 |
| January | 7.3 | 2 | 1.9 | 0.7 | 2.8 | 5.1 | 7 |
| February | 8.6 | 2.1 | 2 | 0.7 | 2.9 | 4.5 | 2 |
| March | 8.4 | 2.3 | 1.9 | 0.8 | 3 | 4.7 | 3 |
| April | 9.8 | 1.2 | 1.6 | 0.6 | 2.2 | 4.3 | 1 |
| May | 11.1 | 0.2 | 0.8 | 1.4 | 2.6 | 3.8 | 3 |
| June | 10.2 | 0.2 | 0.5 | 1.3 | 2.4 | 3.4 | 1 |
| July | 9.4 | 0.3 | 0.6 | 0.2 | 1.2 | 3.6 | 0 |
| August | 1.4 | 0.2 | 0.2 | 0.2 | 0.8 | 0.9 | 0 |
| September | 1.9 | 1 | 0.7 | 0.3 | 0.9 | 1.5 | 3 |
| October | 3.5 | 1.2 | 1.2 | 0.2 | 1.2 | 2.5 | 2 |

Table 2.6: The number of sessions of each training activity per week and relationship to injury rate.

2.5.9 Severity of injury.

Severity of injury was established by the number of training and racing hours lost due to injury as in the RIPP study (Waller et al., 1994) The number of hours completed by the injured subjects was compared to the mean number of hours completed by the non-injured cohort. While 54.5 % of the injuries reported resulted in the subjects losing training hours, the remaining reported injuries resulted in the subjects completing more training hours than the mean completed by the non-injured group. Table 2.7 represents individual injuries and the number of injuries to each area that resulted in the subjects completing increased or decreased racing and training.

| Site | Type | Change in exposure hours as a result of injury. | |
|------------------|--------------------------------|---|-------------|
| | | Increased | Decreased |
| Ankle | Tendinitis | 1 | 1 |
| Cervical spine | Facet Joint disorder | 4 | 1 |
| Calf | Tendinitis | | 1 |
| Foot | Fracture | 1 | |
| Knee | Patellofemoral joint syndrome. | 3 | 4 |
| | Lumbar spine | | 1 |
| Lumbar spine | Contusion | | 1 |
| | Disc injury | 2 | 2 |
| | Facet joint disorder | 2 | 5 |
| Shoulder | Muscle strain | 2 | |
| | Tendinitis | 1 | 1 |
| Sacroiliac joint | Dysfunction | | 3 |
| Thoracic spine | | 1 | 2 |
| Thigh | Muscle strain | 1 | 1 |
| | Compartment syndrome | 1 | |
| Wrist | Tendinitis | 1 | 2 |
| | Total injuries | N=20 | N=24 |

Table 2.7: Individual injuries and proportion that increased or decreased training or racing as a result (N = injury incidents)

Table 2.7 shows that injury either resulted in an increase in exposure (combined training and racing) hours or a decrease. Of the 5 cervical spine injuries reported, all but 1 injury

incident actually resulted in the subject completing more training and racing hours than when not injured. Only sacroiliac dysfunction resulted in the reduction (only) of exposure hours.

Lumbar spine injuries were examined specifically. Training hours of the injured participants were compared to the mean that were completed by the non-injured cohort in that month. The minimum training that was completed was 49.63% of the mean hours and was a result of a lumbar facet joint injury (see table 2.8). Cervical injury resulted in subjects being able to complete from 97% to 147.3% of mean training hours. The mean value for this group was 116% of ‘normal training hours’ completed.

| Injury type | Training and racing hours completed by injured subject | Training and racing hours completed by whole cohort | % of mean training | +/- change in training (%) |
|---------------|--|---|--------------------|----------------------------|
| Contusion | 49 | 63.2 | 77.5 | -22.5 |
| Disc | 40.7 | 79.1 | 51.4 | -48.5 |
| Disc | 68 | 63.3 | 107.4 | 7.4 |
| Disc | 92 | 64.3 | 143.1 | 43.1 |
| Disc | 50.5 | 56.4 | 89.5 | -10.5 |
| Facet joint | 97.7 | 79.1 | 123.6 | 23.6 |
| Facet joint | 78 | 79.1 | 98.7 | -1.3 |
| Facet joint | 52.5 | 79.1 | 66.4 | -33.6 |
| Facet joint | 52.4 | 64.3 | 81.5 | -18.5 |
| Facet joint | 61.4 | 66.7 | 92.1 | -8 |
| Facet joint | 33.1 | 66.7 | 49.6 | -50.4 |
| Facet joint | 44.5 | 35.3 | 126.2 | 26.2 |
| Muscle strain | 67.4 | 63.3 | 106.5 | 6.4 |
| Muscle strain | 26.8 | 25.1 | 106.8 | 6.8 |

Table 2.8: Number of training hours completed in month of injury by subjects who sustained lumbar spine injury.

2.5.10 Injury recurrence

Baseline reports (retrospective injury data) were compared to prospective data and it was shown that of the 13 participants who sustained a new lumbar spine injury, 7 had reported an injury in the same region in the previous season. Only 3 of the participants who sustained a lumbar spine injury in the season prior to the study did not re-injure the same area during the study period.

2.5.11 Sweep versus sculling injuries.

The injuries of sweep rowers (row with one oar, rotating to the right or left of the boat) compared to scullers (row with 2 oars) are represented in table 2.8. Although there were more injuries to ‘scull only’ rowers, when this was adjusted for the number of subjects in each category the differences were not significant (χ^2 with 2 df = 2.32, $P=0.32$). When the spinal injuries were subdivided into lumbar, cervical and thoracic, the numbers were too small for analysis.

| Boat type | Subjects | Total number of injuries | Number of lumbar spine injuries | Number of cervical spine injuries | Number of thoracic spine injuries |
|------------------------|----------|--------------------------|---------------------------------|-----------------------------------|-----------------------------------|
| <i>Scull only</i> | 10 | 27 | 8 | 5 | 1 |
| <i>Sweep only</i> | 8 | 14 | 5 | 0 | 2 |
| <i>Scull and sweep</i> | 2 | 3 | 1 | 0 | 0 |

Table 2.9: Comparison of injury rates in scullers and sweep rowers.

2.5.12 Relationship between ergometer training and lumbar spine injury.

The number of sessions per week of ergometer training completed by participants was analysed. Rowers who sustained a lumbar spine injury during the study period performed on average 35 sessions (95% CI 3 to 65) per year more than their non injured counterparts ($t = 2.11$, $df = 18$, $P=0.049$).

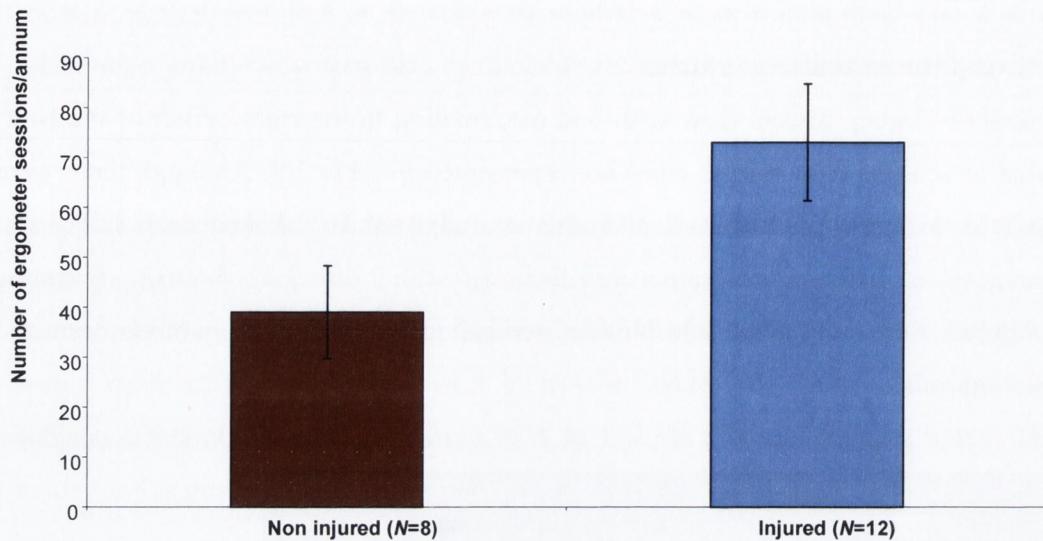


Figure 2.3: Mean ergometer sessions over twelve months for rowers with and without a lumbar spine injury (with SD).

2.6 DISCUSSION

2.6.1 Injury definition.

The definition selected for this study was adapted from the RIPP study (Waller et al., 1994) and reflects a sport which involves regular competition, i.e. rugby. However, the results of this study suggest that only one of the subcategories defined injury. Races in rowing are so infrequent that only one injury caused a subject to miss racing. It is also clear when examining training hours lost to injury, that many rowers actually complete more hours when injured which is reflective of the large volume of cross training completed by rowers, particularly in winter months. The study suggests that injury caused the rower to *change* training rather than reduce hours. Thus for future studies, the most accurate definition may be noted by a visit to a health professional. This narrow definition has been used previously in examination of injuries in amateur horse racing where competition or racing is also very infrequent (Balendra et al., 2007) and may be the most appropriate in rowers.

2.6.2 Injury incidence.

The primary aim of this study was to establish an injury rate in international rowers over a 12 month period and this was found to be 3.67/1000 hours of combined training and competing, with a mean of 2.2 (1.24) injuries sustained by each athlete over the 12 month period. Comparison of the rate of injuries sustained by the study subjects with previous work is difficult, primarily because of the lack of published prospective cohort studies in rowing. The incidence of injury is higher than that reported in the only study which prospectively reported injury incidence at 1.5/1000 hours (Parkkari et al., 2004) although, as this study was done on a normal population, comparison with full time international athletes is not meaningful. Two studies established retrospective injury incidence at 2.1/1000 hours (Smoljanovic et al., 2009) and 0.4/1000 rowing hours and 4/1000 land training hours (Budgett and Fuller, 1989) although the different methodologies in these studies mean that the hours of training were only estimated. However, this study suggests that the injury incidence may be higher than previously thought.

The injury rate of 3.67/1000 hours of contact with rowing competition and training is higher than that in distance running at 2.5/1000 hours and lower than middle distance running and sprinting at 5.6 to 5.8/1000 hours (Wiklander, 1987). Although rowers race over 2 km which would take between 6 and 8 minutes in international athletes, much of their training, particularly during the winter season is based on building endurance so the rate may be more closely compared with distance running. The results of this study are also higher than that of volleyball at 2.6/1000 hours (Verhagen et al., 2004) which is not a contact sport but involves rapid and forceful movements of the body both horizontally and vertically, unlike rowing which involves a rhythmical movement which is controlled by the athlete suggesting that the lack of a surprise element may make rowers less injury prone and therefore these results a little surprising. When rowing is compared with another water sport, it demonstrates a lower injury rate. Analysis of sailing injuries found a higher injury rate at 8.8/1000 hours although a proportion of these injuries included impact with boat hardware (Neville et al., 2006).

A notable finding of this study was the volume of time spent training (mean of 645.3 hours) compared to competing (mean of 3.07 hours) and that none of the injuries reported were sustained during competition. When compared to other sports with a very high training to competing ratio such as boxing, rowing injury rate is higher than boxing which

reports an injury rate of 2/1000 hours (Zazryn et al., 2006). In addition to this, when training only injuries were analysed in professional rugby rowing had a higher injury rate, with rugby demonstrating a training injury rate of 2/1000 hours (Brooks et al., 2005). Although the injury rate established in this study is not as high as that in collision or contact sports such as soccer (9.4/1000 hours), (Walden et al., 2005) and Gaelic football (13.5/1000 hours), (Wilson et al., 2007), this is not always the case and some contact sports report a lower injury rate (Giza et al., 2005). When rowing is compared to sports with similar training to competing ratios and which do not involve collision with other athletes, the injury rate is comparatively high.

2.6.3 Area and type of injury.

The area in which injury was most frequently reported was the lumbar spine which constituted 31.82% of total injuries reported and this is in agreement with previous studies which reported lumbar spine as the area most frequently injured in rowers (Smoljanovic et al., 2009, Coburn and Wajswelner, 1993, Hickey et al., 1997, Edgar, 1993, Budgett and Fuller, 1989). The results of this study are similar to the most recently published study (retrospective) on a comparable cohort (Smoljanovic et al., 2009) which found lumbar spine injury to constitute 32.3% of total reported injuries.

Although low back pain is a common injury in the general population with a lifetime incidence frequently reported, it must be noted that injuries were all new, within a 12 month period, and were directly as a result of rowing training or competing. This study found that 65% of the cohort sustained a lumbar spine injury during the 12 months of the study. This may be compared with studies of the general population which examined incidence of lumbar spine pain over a 12 month period. Prevalence ranged from 49.1% of the population (Palmer et al., 2000) to 25.3% (Croft et al., 1999). It appears that the incidence in rowers is considerably higher. The results in this study were reported as *incidence*, i.e. they were all newly reported injuries during the 12 month study period. If *prevalence* were reported in this group, as in the studies of Palmer et al., and Croft et al., the number may actually be greater. Lumbar spine pain is a debilitating injury and such a high incidence should be considered carefully, particularly as all the cohort were full time professional athletes and as such could consider the injury to be occupational. The study highlighted that although high volumes of 'core stability' training were completed by the cohort, it did not seem to have a protective effect on the lumbar spine. There is disparity in description of 'core stability' training with no clear definition given in the study, although

specific exercises were given on the IARU programme. It may have been interpreted differently by study subjects as they were simply required to complete number of hours of 'core stability' training.

The second most common injury cited was to the knee which, at 15.9% of total injuries is slightly higher than that previously reported at 12.9% (males) and 9.3% (females) (Hickey et al., 1997), although comparison should be made with caution due to the different cohort profile and study methodology.

Most striking was the high number of cervical spine injuries reported at 11.4% of total injuries. Injuries have been previously reported to the cervical spine at 1.7% (male) and 1% (female) of total injuries reported with total injuries to the spine reported as 34% (male) and 23.1% (female), (Hickey et al., 1997) . However, while this finding is notable, it must be interpreted appropriately as the severity of such injuries are impossible to interpret clearly with the present methodology. More research is needed in this area.

The findings of this study demonstrated that 50% of injuries were to the spine which is much higher than previously reported and it was further noted that 31.8% of injuries reported were facet or apophyseal injuries to the spine or that 11.4% of injuries were lumbar disc injury. Such injuries are complex and successful management of such can be much more challenging than muscle or ligament tears presenting the rowers with greater risk of not recovering fully from injury. However, it must also be noted that a considerable proportion of spinal injuries were diagnosed as facet joint injuries, based on clinical examination alone. Such an injury would be commonly diagnosed by a physiotherapist with manual therapy training as a result of examination findings which included: stiff and/or painful cervical rotation and side flexion in particular; unilateral presentation of pain; pain and/or stiffness of intervertebral accessory motion of the facet joint on palpation. As with many injuries noted in the study, accuracy could be enhanced with confirmation of clinical hypothesis with the aid of tools such as imaging and this should be considered for further studies. Of note, there were no reported incidences of stress fractures in the ribs of the cohort which has previously been reported as between 12.9%, 22.6% (Hickey et al., 1997) and 8.7% (Dragoni et al., 2007) of total reported injuries. The fact that wrist injuries were merely reported as tendinitis provides limited information as clinical observation would present a more specific diagnosis of de Quervains tenosynovitis in rowers (Secher and Volianitis, 2007). Further studies would benefit from more comprehensive diagnosis.

The fact that 79.5% of the injuries were new or non-recurring seems to be high considering that the international rowers in this group would have been exposed to a high training volume over a number of years. It is expected that more injuries would have been experienced previously as risk factors should be similar. However this may have been an unusual year, (Olympic Games year) and most of the athletes had progressed from full or part time employment or study, to full time training in this year and it is likely that training volumes had increased for many. Without previous exposure data it is not possible to determine if such a transition was a major risk factor for injury but would merit further study. The number of injuries in this study was higher than reported for the 12 months prior to the study onset. A total of 34 injuries were reported by the study cohort in the previous 12 months (retrospective baseline data) which compares to 44 during this study, representing an increase in 33%. This increase may be a result of increased training but cannot be compared accurately due to lack of exposure data. The most common injury reported in the baseline data was to the lumbar spine (29% of injuries in previous 12 months compared to 31.8% of injuries in the present study) which is consistent with previous studies and compares closely to the present study. All injuries were reported as a new incident so this does not represent repetition of data.

2.6.4 Time of injury and risk factors.

The highest number of injuries occurred during winter training in November, December and January with another peak in September. This was similar to a previous finding (Hickey et al., 1997), which also found another peak in May and June. However, this should be viewed with caution as it was conducted in the southern hemisphere and may have been due to a different type of training and racing schedule. November, December and January are traditionally associated with a lower volume of boat training and more land training due to weather and day light restrictions associated with the winter months in Ireland, suggesting that land rather than boat training presents increased risk of injury for rowers.

Although the highest injury rate was in November (31.8% of all reported injuries) which also corresponded with the time of the highest volume of training in terms of contact hours, this was a non significant association. This is in contrast to previous studies (Gabbett and Domrow, 2007), which demonstrated that each arbitrary unit increase in training load increases the odds of injury. However, a significant correlation was found between time

spent ergometer training, heavy weight training and core stability training and risk of injury. Ergometer training and heavy weight training have been previously cited as injury risk factors in earlier studies (Teitz et al., 2002), although core stability training is a surprising finding as it is traditionally introduced into programmes in an effort to stabilise the trunk and reduce injury risk, particularly to the spine. However, there is a lack of consensus as to what constitutes 'core stability training' (Standaert and Herring, 2007) and the term has been interpreted widely. Future research should include a clear definition of this type of training to reduce ambiguity. Such training can vary from low load spinal stability exercises to high load strengthening exercises for the trunk, which may explain this finding and which merits further study in this area. If indeed such training is implicated in injury to the lumbar spine it clearly contradicts the reason why it was introduced into the training programme; i.e. to *reduce* injury risk.

Time spent ergometer training had the most significant correlation with injury onset and this confirms biomechanical observations that the loading to the joints in ergometer sessions is different to the patterns seen on the water (Lamb, 1989, Dawson et al., 1998). The fact that those who sustained a lumbar spine injury completed significantly more ergometer sessions per year ($P=0.049$) than those who did not, is further confirmation that such a method of training may be associated with onset of this injury. This finding highlights the need for further research, particularly as rowers traditionally spend many hours training on the ergometer and also because the ergometer is frequently used as a selection tool by coaches and team managers. In general, the findings suggest that further investigation into rowers' land training methods is warranted and the risk versus benefit ratio should be considered, particularly when considering lumbar spine injury.

2.6.5 Severity of injury.

One of the most notable findings from the study was that time lost from racing or training was a very poor indicator of injury severity. Time lost was selected as the outcome measure as it is seen frequently in sports injury epidemiology, including the RIPP study. Many injured subjects were able to complete more than the mean training volume completed by the non-injured cohort. There are a number of likely reasons for this finding. Most of the injuries were sustained in the winter months when the largest volume of cross training takes place. It is likely that injured subjects replaced one type of training with another when injured, in a bid to maintain fitness in such an important training and selection year. More intense sessions such as heavy weight training are likely to be

replaced by an aerobic based session in an injured subject which may, by definition, involve more time but less intensity. Thus a more accurate picture of injury severity would be given by exact analysis of how the injury results in training programme change from that scheduled in terms of intensity, frequency and duration. The severity of cervical spine injury is poorly represented in this study as, although all subjects reporting this injury fulfilled the required definition, all but one subject actually completed *more* than the mean training hours. When the lumbar spine in particular is examined, it is surprising that subjects with a lumbar disc injury are able to complete such large volumes of training. This may suggest inaccuracy in diagnosis but would be clarified in future studies by a more comprehensive analysis of the effect of injury on training patterns rather than volume.

2.6.6 Sweep versus sculling injuries.

The ratio of sweep to sculling injuries is a little surprising. The rotational aspect of sweep rowing, which is hypothesised to load the lumbar spine greater than in sculling, has frequently been noted as a risk factor for injury by clinicians. The data does not appear to support this with a similar number of scullers sustaining lumbar injuries. It is notable that only scullers sustained cervical spine injuries. A reason for this could be that steering demands on scullers require them to look behind them at regular intervals, thus rotating their cervical spine. However all rowers in the cohort trained in 'coxless' boats meaning that more individuals than the scullers were steering boats.

2.6.7 Limitations of the study.

Although the sample size in this study is smaller than those seen in injury surveillance in sports such as soccer and rugby, this number is representative of a full international rowing team of a moderately sized rowing country, and as such was a representative sample of international standard. The lack of such a previous study merited commencement of this project and the sample size would be similar to previous studies which are the first to conduct a prospective cohort study in other sports (Verhagen et al., 2004, Neville et al., 2006). Another limitation was that although the study was prospective, interviews on a monthly basis may have introduced an element of recall bias. The athletes were required to recall 4 previous weeks of activity at each interview. However, telephone interviews were the most cost effective as the athletes were frequently out of the country attending training camps. Such a study method had been previously published (Walden et al., 2005). However, all athletes kept training diaries and were given a training schedule by their

coach that only changed on a monthly basis so it was assumed that exposure data was accurate. Future studies would merit a web-based system which would allow weekly exposure and injury data to be recorded.

2.6.8 Indications for further study.

This study highlighted that lumbar spine injury is the most common injury in rowers. Furthermore, ergometer training was significantly associated with injury onset. There is a need to investigate ergometer training in the context of lumbar spine injury. Comparison of lumbar spine kinematics in the boat and on an ergometer may provide more clarity regarding this association.

Repetition of such a study in the future on a larger and diverse cohort is recommended to provide more comprehensive data regarding rowing injuries. A weekly web based system would reduce recall bias and a web based system with accessory imaging and diagnostic tools would increase accuracy in injury reporting for clinicians. Clear definitions of training types, in particular core stability, would allow more accurate analysis of injury predictors. The limitations of the injury definition used in this study have been discussed and future studies in rowing cohorts should include a definition that examines *changes* in training types rather than missed training sessions, or match absence.

2.7 CONCLUSION

This study examined injury profile in international rowers during an Olympic year. The study demonstrated that international rowers are exposed to a very high training volume and low competition experience and are at higher risk of injury than that reported in many non-contact sports and some contact sports. The high risk of lumbar spine injury and the significant association of high volume of ergometer training to injury risk, merit further research to reduce time and competition lost to injury.

2.8 SUMMARY OF OBJECTIVES FOLLOWING STAGE ONE.

√ = Completed

X = Not yet completed

- To establish an injury profile and identify predictors for injury in rowers √.
- Determine the frontal plane kinematics of the lumbar spine when rowing X.
- Compare the frontal plane kinematics of the lumbar spine when rowing in a boat with rowing on an ergometer X.
- Compare the sagittal plane kinematics of the lumbar spine when rowing in a boat with rowing on an ergometer X.
- Examine kinematics of lumbar spine in both the frontal and sagittal plane under the conditions of fatigue X.
- Compare the kinematics of the lumbar spine when rowing in a boat with rowing on an ergometer, under the conditions of fatigue X.

The following flow chart represents the progression of research following study 1.

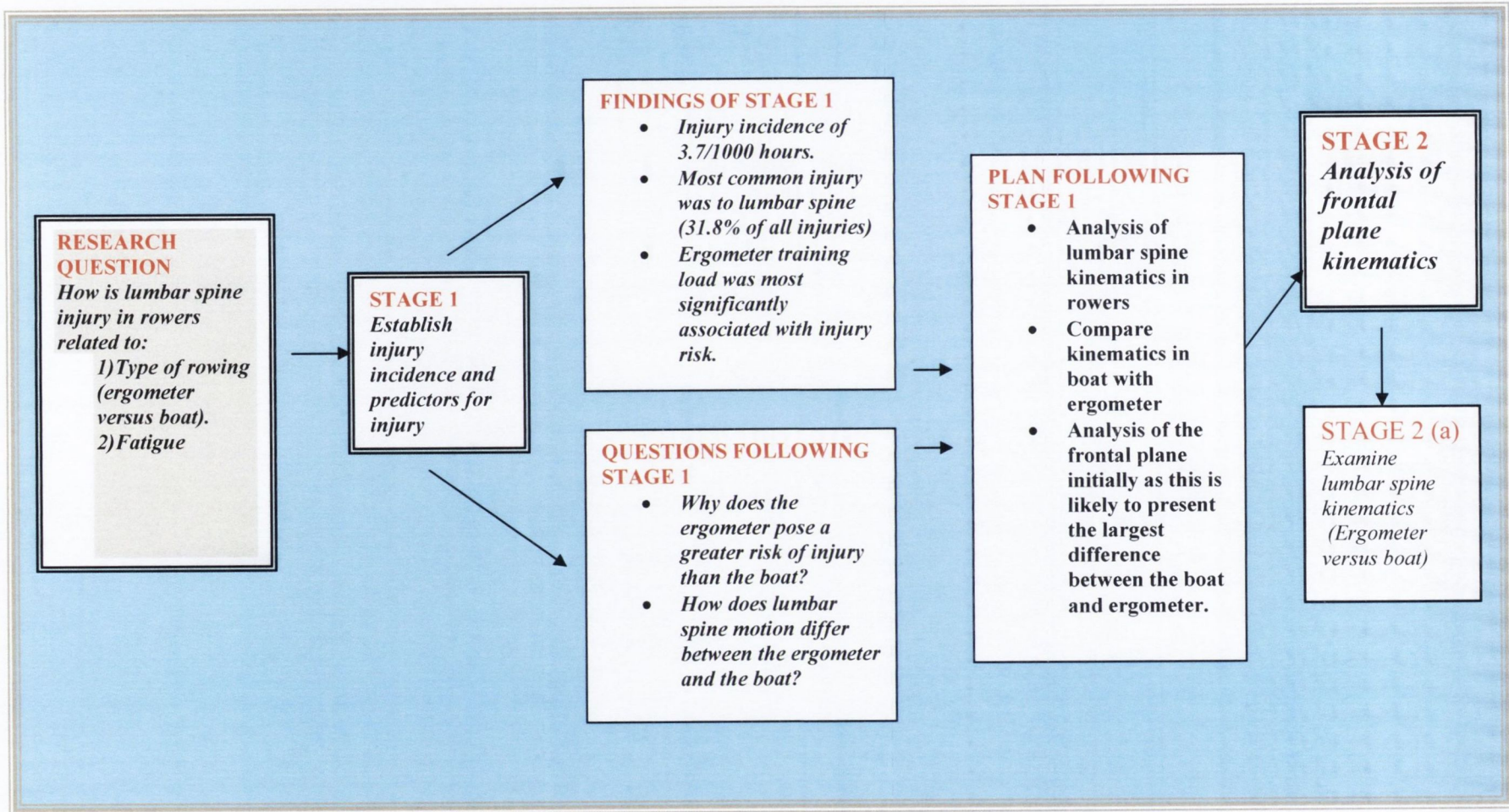


Figure 2.4: Flow chart to show the progression of research following study 1.

CHAPTER 3

STUDY 2

A STUDY TO MEASURE FRONTAL PLANE ANGULAR CHANGES IN THE LUMBAR SPINE OF ELITE ROWERS: A COMPARISON OF ERGOMETER AND BOAT ROWING.

3.1 ABSTRACT.

Objective: To determine frontal plane kinematics in the lumbar spine of elite rowers during ergometer and boat rowing.

Methods: Five elite rowers, all male, mean age 18.6 (0.89) years were the participants in this study. Lumbar spine kinematics were measured in the frontal plane at L3 during two rowing trials; one in a sculling boat and one on an ergometer. The trial comprised a ten minute 'anaerobic threshold' 'piece of rowing' at a stroke rating of 28/minute and a heart rate of 85% of maximum. Spinal kinematics were measured at a sample rate of 50Hz throughout the rowing trial using a Spectrotilt inclinometer connected to a Biometrics DataLog system. The inclinometer was attached directly over the spinous process of L3.

Results: Frontal plane angular displacement was found at L3 with reference to horizontal throughout the boat and ergometer trials. The values reached between 34% and 71% of full maximum available range (normative data found in previous studies). The mean frontal plane angular displacement at L3 was 5° on the ergometer and 3.4° in the boat although this was a non-significant difference. The angular displacement increased over the course of the ergometer trial by a small amount (0.9°) which was not significant ($P=0.11$). The angular displacement decreased over the course of the boat trial by a small amount (0.4°) which was not statistically significant ($P= 0.55$).

Conclusion: This study found that a notable level of frontal plane angular displacement takes place in the lumbar spine during rowing. Differences between ergometer and boat rowing were observed, with ergometer rowing causing increased values of displacement than boat rowing. Further research is required to investigate this further.

3.2 INTRODUCTION.

Study 1 (chapter 2), found that lumbar spine injury is the most common injury in rowers and found that the factor that was significantly associated with lumbar spine injury in this cohort was ergometer training compared to boat training (section 2.5.8).

To understand why ergometer rowing presents a greater risk for injury than boat rowing, lumbar spine kinematics in both these situations should be compared. Section 1.6.1 reviewed a number of studies which examined lumbar spine kinematics on a rowing ergometer. All the studies which were reviewed, examined kinematics in the sagittal plane only as this is the range where most movement takes place. Both ergometer and boat rowing are likely to show similar results in spinal sagittal plane profiles as both allow the same movement pattern in this plane i.e. the lumbar spine flexes forwards and backwards from the catch to the finish position. However, when the ergometer and boat are compared, movement in the frontal plane is likely to be different. The boat has a curved under surface (see Figure 1.0) which means that it moves from side to side when the rower sits on it in the water (an unstable surface); it should therefore allow considerable movement in the frontal plane. The Concept 2 ergometer has a fixed flat base (see Figure 1.3) and is placed on a stable surface (the ground) and thus should allow minimal movement in the frontal plane. This may be one of the clearest differences between ergometer and boat rowing and justifies why frontal plane kinematics should be measured in the rower in both cases.

There is therefore a need to compare spinal kinematics of the lumbar spine in boat and ergometer rowing to understand why ergometer rowing places an increased risk of injury. The greatest difference between the boat and ergometer is likely to be seen in the frontal plane and thus this plane of motion should be examined first. As the studies reviewed in section 1.6.1 showed that sagittal plane motion in the lumbar spine increases as rowers fatigue; there is a need to examine if the same pattern is observed in the frontal plane.

3.3 AIM AND OBJECTIVES.

Aim

The aim of this study was to determine the frontal plane kinematics of lumbar spine when rowing.

Objectives

- To compare the frontal plane kinematics of the lumbar spine when rowing in a boat with rowing on an ergometer.
- Compare the kinematics of the lumbar spine when rowing in a boat with rowing on an ergometer, under the conditions of fatigue.

3.4 METHODS

3.4.1 Participants

The subject group examined in this study were male elite rowers, mean age 18.6 (0.89) years. All were training and competing as part of the Commercial Rowing Club Senior Sculling Group. Ethical permission was granted for this study from the Trinity College Faculty of Health Sciences Research Ethics Committee and informed written consent was obtained from all participants. Participants in the study were provided with full details of the study and signed a consent form confirming enrolment in the study and acknowledged the confidentiality of their personal details. Inclusion criteria were: Over 18 years of age; Training and competing at senior (elite) level rowing; Training at least 5 times/week; No history of lumbar spine injury in the previous 6 months.

The head coach of Commercial Rowing Club, Dublin was contacted by telephone and asked to invite members of the senior sculling group ($N = 8$) to take part in the study. Those who were interested were provided with full details of the study and consent forms.

3.4.2 Instrumentation.

Analysis of frontal plane angle changes was measured at a sample rate of 50Hz throughout the rowing stroke using a Spectrotilt RS232 Electronic Inclinometer (Spectron Systems Technology Inc. New York, USA), see Figure 3.1. This was connected to a Biometrics DataLog (Biometrics P3X8, Biometrics Ltd, UK), see Figure 3.2. Before use, the Spectrotilt inclinometer was calibrated in a study completed by Dr Ciaran Simms, Department of Mechanical Engineering, Trinity College Dublin (see Appendix C). The calibration study showed that the Spectrotilt Electronic Inclinometer sensor is suitable for

measurement of rowing motion with a frequency of up to 1Hz when a low pass filter of 1.35 Hz is applied. Within these limits the maximum error appears to be of the order of 0.5°, and the motion is very well captured and the sample rate of 50 Hz was appropriate for the data required and the system was valid for such a study.



Figure 3.1 Spectrotilt RS232 Electronic Inclinometer (www.spectronsensors.com).

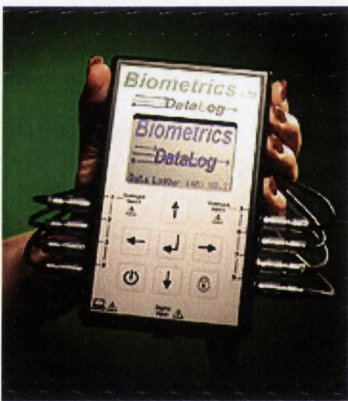


Figure 3.2 Biometrics DataLog (www.biometricsltd.com)

3.4.3 Protocol.

The Spectrotilt inclinometer was attached to the skin of the rower on the spinous process of L3 as this is the mid point position of the lumbar spine. Superglue (Loctite Superglue Gel Professional, Loctite ® Brand Henkel, Ohio, USA) was placed on the surface of the inclinometer which was then placed on the skin and further secured with zinc oxide tape. A lead connected the inclinometer to the Biometrics DataLog which was placed in a small back pack on the rower's upper back. The back pack was small and light and allowed the rower to be active without any change in their normal technique. Prior to the test, the

participant sat upright on the ergometer or on the jetty before entering the boat, with knees extended in the 'finish' position. This position was selected as the neutral position of the lumbar spine and the equipment was set at zero degrees. All angular displacement recordings were made relative to this zero position with the subject in a sitting position. Thus the L3 angle measured in this study was measured relative to a fixed horizontal reference point (the ground).

Following a 5 minute warm-up (Mackenzie et al., 2008), the subject performed an 'anaerobic threshold' piece of rowing, rating 28 strokes/minute and with heart rate at 85% for 10 minutes. Heart rate was measured by short range telemetry (Polar Electro, Finland). Analysis of frontal plane angle changes was measured throughout the rowing stroke using the Spectrotilt inclinometer. The sampling rate of the system was 50 Hz with a settling time of 300ms as demonstrated in the previous calibration (Appendix C). The test was carried out first on a Concept 2 model C rowing ergometer (Concept Inc., Vermont, USA). The test was then repeated in a single sculling boat, on the same stretch of river in the same direction to reduce the effects of a flowing tide. All sculling boats complied with FISA rules of racing, part IV (see Appendix D). Wind speed was measured using a Kestrel 1000 (Nielsen Kellerman, USA) wind speed monitor to ensure that wind speed was less than 10 kph/hr during all tests.

Data was entered into Biometrics software package (Biometrics Ltd Version 3) and was converted to an ASCII file. It was then entered into Microsoft Excel and was low pass filtered at 1.35Hz (see Appendix C). A graph was produced of a series of peaks and troughs for the 10 minutes of rowing. The first five points at 100s, 300s and 500s were selected on each graph as this represented the beginning, middle and end of the rowing session. The total displacement (peak to trough value) was measured for each point and the mean value of the five points was calculated. The peak to trough value represented the total frontal plane movement.

3.4.4 Statistical analysis.

Data was analysed with SPSS v15. Paired t-tests were performed to analyse differences in displacement between the angular change in the boat and that on the ergometer. A paired t-test also examined change in angular displacement between the first and last stage of the test on the ergometer and then the boat. Alpha level was set at $P < 0.05$.

3.5 RESULTS

For each subject, a chart was produced for the test on the ergometer and the sculling boat. The charts for subject 1 are shown in figure 3.3 and 3.4. Charts for the other subjects may be viewed in Appendix E. It may be observed that as the participants started each test, they deviated from the original zero position to continue the test in this deviated situation. In practical terms, they side flexed slightly to one side throughout the test although it is not possible to tell from the data if this was to the right or left.

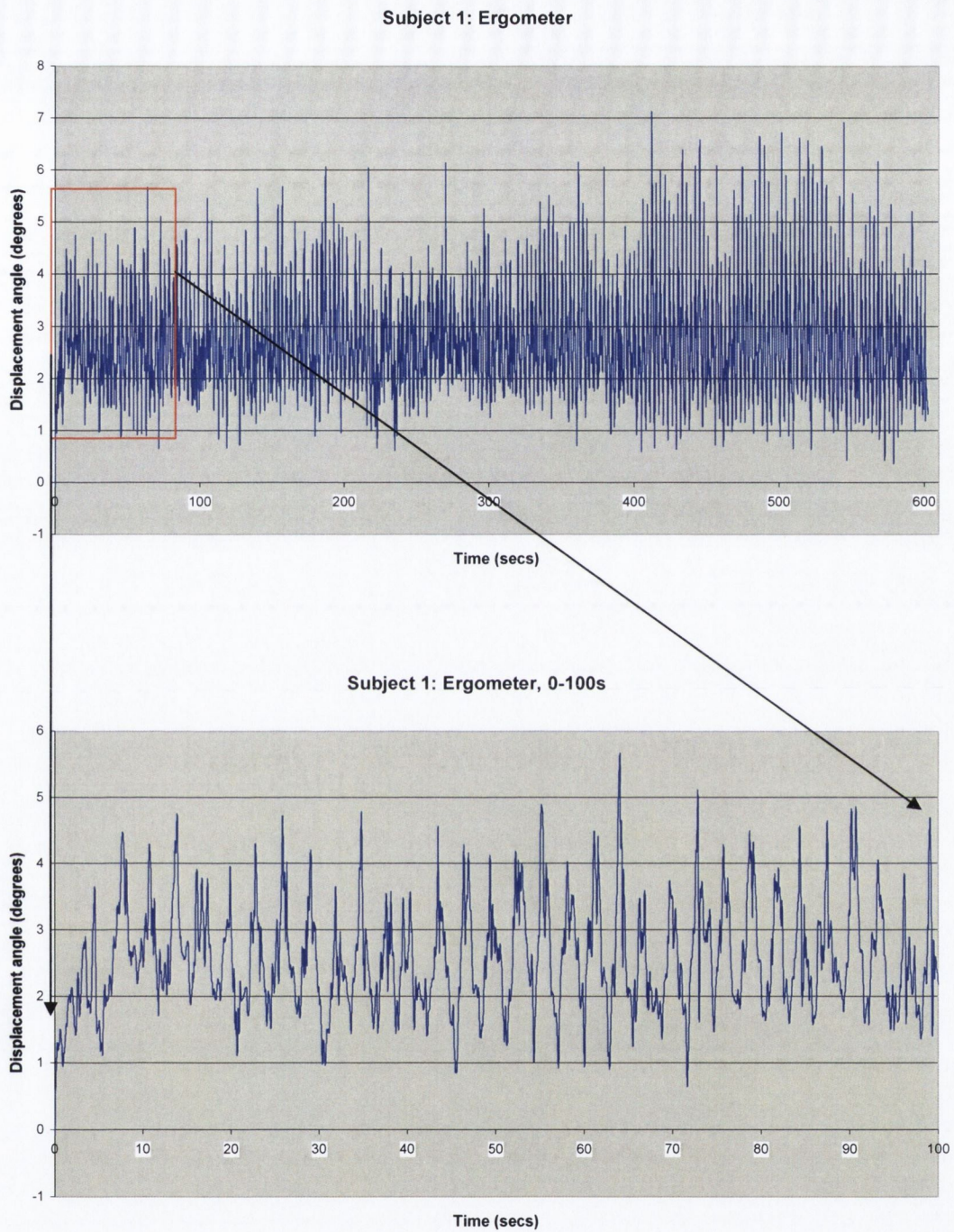


Figure 3.3: Chart for subject 1 showing frontal plane angular displacement at L3 over a 10 minute rowing protocol on the Concept 2 ergometer with first 100 seconds magnified.

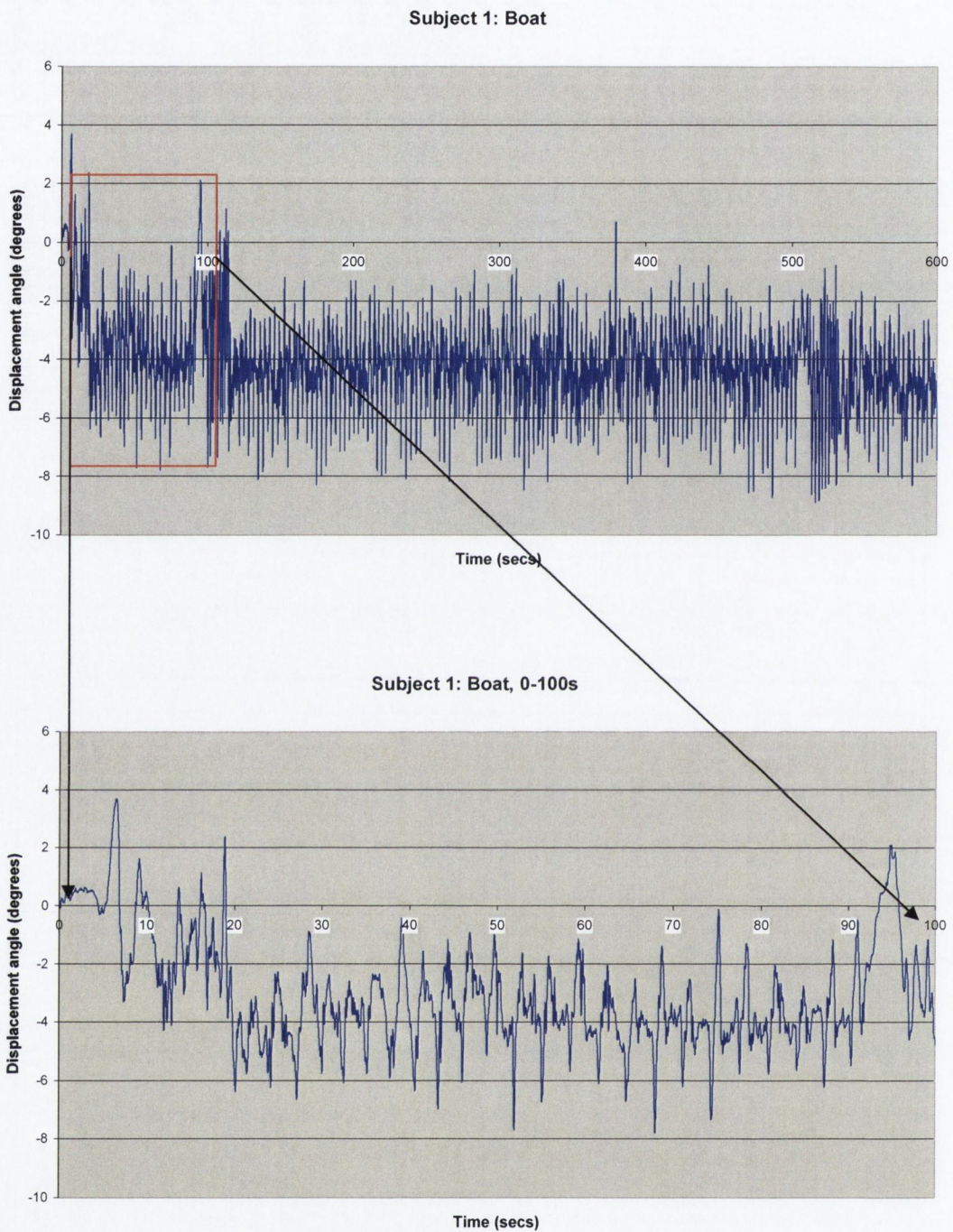


Figure 3.4: Chart for subject 1 showing frontal plane angular displacement at L3 over a 10 minute rowing protocol on the water in a sculling boat with first 100 seconds magnified.

Each chart shows the full frontal plane motion for each cycle. The movement that takes place in the frontal plane at L3 is more commonly known as side flexion of that segment. The peak of the cycle represents full side flexion of L3 to one side and the trough represents full side flexion to the other side.

3.5.1 Findings from the ergometer trial.

For each subject, the mean frontal plane angular displacement value for the three time intervals (100, 300 and 500 seconds) was calculated. Values for all five subjects are shown in Table 3.1.

| Concept 2 ergometer | | | | |
|----------------------------|----------------|------------------------------------|------------------------------------|------------------------------------|
| | Subject | mean displacement (degrees) | mean displacement (degrees) | mean displacement (degrees) |
| | | 100s | 300s | 500s |
| | 1 | 2.5 | 2.3 | 4.6 |
| | 2 | 2.5 | 2.4 | 4.0 |
| | 3 | 7.3 | 7.6 | 7.5 |
| | 4 | 5.6 | 4.0 | 6.5 |
| | 5 | 4.6 | 8.8 | 4.3 |
| Mean | | 4.5 | 5.0 | 5.4 |
| Sd | | 2.1 | 3.0 | 1.4 |

Table 3.1: Mean frontal plane angular displacement values for 3 time intervals for the Concept 2 ergometer trial.

Although there was a small increase in angular displacement between the first (100s) and last (300s) stages of the test, a paired t-test showed that this was not significant ($P=0.11$).

3.5.2 Findings from the boat trial.

As for the ergometer trial, values were compared between subjects for the 3 various time intervals and the results are shown in Table 3.2

| Boat | | | | |
|-------------|----------------|------------------------------------|------------------------------------|------------------------------------|
| | Subject | mean displacement (degrees) | mean displacement (degrees) | mean displacement (degrees) |
| | | 100s | 300s | 500s |
| | 1 | 2.5 | 4.9 | 3.7 |
| | 2 | 5.4 | 1.0 | 2.9 |
| | 3 | 3.7 | 3.9 | 3.2 |
| | 4 | 3.1 | 2.7 | 0.6 |
| | 5 | 3.1 | 5.7 | 4.7 |
| Mean | | 3.6 | 3.6 | 3.0 |
| SD | | 1.1 | 1.9 | 1.5 |

Table 3.2: Mean frontal plane angular displacement values for 3 time intervals for the boat trial.

There was a small decrease in mean angular displacement between the first (100s) and last (300s) stages of the test , a paired t-test showed that this was not significant ($P=0.55$).

3.5.3 Comparison of findings from the ergometer trial with the boat trial.

The findings for the three time periods were compared for the two types of rowing trial (ergometer and boat). The results are shown in Table 3.3.

| | 100s boat | 100 s C2 | 300s boat | 300s C2 | 500s boat | 500s C2 |
|----------------|---------------------------------------|----------------------------|------------------|----------------------------|------------------|----------------------------|
| Subject | Average displacement (degrees) | | | | | |
| 1 | 2.5 | 2.5 | 4.9 | 2.3 | 3.7 | 4.6 |
| 2 | 5.4 | 2.5 | 1.0 | 2.4 | 2.9 | 4.0 |
| 3 | 3.7 | 7.3 | 3.9 | 7.6 | 3.2 | 7.5 |
| 4 | 3.1 | 5.6 | 2.7 | 4.0 | 0.6 | 6.5 |
| 5 | 3.1 | 4.6 | 5.7 | 8.8 | 4.7 | 4.3 |
| Mean | 3.6 | 4.5 | 3.6 | 5.0 | 3.0 | 5.4 |
| t-test | | $P=0.45$ | | $P=0.28$ | | $P=0.12$ |

Table 3.3: Comparison of mean frontal angular displacement values for ergometer (C2) and boat rowing.

For each time period, it can be observed that the mean lumbar spine, frontal plane angular displacement on the ergometer was greater than that for the trial in the boat. A paired t-test was conducted for each time interval with the following results. For the 100 second time period, comparison of boat rowing with ergometer was a non-significant association at $P=0.45$ (95% CI, - 4.07 to 2.19, $t = -0.833$, $df = 4$). For the 300 second time period, the finding was non-significant at $P=0.28$ (95% CI -4.43 to 1.67, $t = -1.25$, $df = 4$). At the 500 second time period the finding was also non-significant at $P=0.12$ (95% CI, -5.62 to 0.9, $t = - 2$, $df = 4$). Thus, although the ergometer rowing caused slightly greater angular displacement for all time intervals, the difference was not significant.

3.6 DISCUSSION.

This study confirms that there is movement in the lumbar spine in the frontal plane during rowing. Previous studies reviewed in section 1.6.1 examined lumbar spine kinematics in rowers, but in the sagittal plane only. Bull and McGregor (2000) reasoned that they only measured sagittal plane kinematics as ‘... no movement takes place in any other spinal planes while rowing on an ergometer’. This study is not in agreement with this observation. This study showed that angular frontal plane displacement values reached as high as 8.8° (subject 3 at 300secs, C2). The mean angular displacement over the three time periods on the ergometer in this study was 5° compared to 3.4° in the boat which indicates that there is a difference even when the margin of error of 0.5° is considered. A number of studies have quantified the maximum side flexion (frontal plane) in normal subjects. Bogduk (2005) found maximum side lumbar flexion at L2/3 and L3/4 to be between 5 and 6 degrees. Li et al., (2009) observed a range of 2.9° (2.4) at L2/3 and 3.4° (2.1) at L3/4. The frontal plane angular displacement observed in this study constituted a combination of total left and right side flexion. If side flexion to one side is assumed to be 50% of the full displacement value, it appears that ergometer rowing causes the lumbar spine to side flex to approximately 2.5° to each side. This represents 50% of the full available range if compared to the findings of Bogduk (2005) or is close to the full available range if compared to the findings of Li et al., (2009). In contrast, boat rowing only caused a mean displacement value of 3.4° and thus single side flexion to be approximately 1.7° which is about 34% of full range if compared to the findings of Bogduk (2005) or between 50 and 71% of full range if compared with the findings of Li et al., (2009). However, comparison of these findings with those of Li et al., (2009) and Bogduk (2005) are simplistic as such data was provided in a very different manner to that in this study, although as a point of

reference it suggests that movement is greater than was previously thought. Thus, this study has demonstrated that there is frontal plane movement in the lumbar spine during rowing.

This study aimed to examine if the lumbar spine angular displacement in the frontal plane differs between the ergometer and the boat. It was logical to expect that greater movement would be seen in the boat as this is an unstable surface (primarily in the frontal plane) compared to the ergometer which sits on the ground. However, this was not the observation in this study. In the boat, the mean angular displacement was 3.6° at 100 secs, 3.6° at 300 secs and 3° at 500 secs; the mean angular displacement decreased by 10.8% over the course of the trial. On the ergometer, the mean angular displacement was 4.5° at 100 secs, 5° at 300 secs and 5.4° at 500 secs; the mean angular displacement increased by 17% over the course of the trial. It should be noted that the difference between the two types of rowing (ergometer and boat) was not statistically significant which may be a reflection of the small sample size in this study. It may also be seen that throughout the course of the trial (as the subject fatigued) the amount of lumbar spine angular displacement increased on the ergometer, whereas it decreased in the boat. Again, this finding was not statistically significant but merits further study on a larger cohort. While the values are not statistically significant, they demonstrate a trend and are greater than the range of error of the equipment of 0.5° noted in the calibration study (Appendix C).

The reasons why the lumbar spine angular displacement in the boat was less than that in the water may be explained by a number of theories. As the ergometer is stable, large values of frontal plane angular displacement will have limited influence on the rower's technique. However, if large movements in the frontal plane take place in the boat, it will become unbalanced and the rowers will find it difficult to row properly. Thus, the boat effectively gives the rower feedback and the ergometer does not. This may be linked in with the proprioceptive system. The boat places greater proprioceptive demands on the rower's trunk than the ergometer; this may help explain why the ergometer is associated with lumbar spine injury. Nolte (2005) noted that a boat is rigged to within millimetre adjustments to allow accuracy; as the rolling of the boat is transferred to the seats that the rowers are sitting on, the rowers shift their bodies through movements in their lower back to try and regain balance. Rowing in a boat is thus likely to stimulate the proprioceptive systems of the lower spine better than ergometer rowing. Good proprioceptive function has been noted to protect joints from injury and numbers of studies have noted that loss of

proprioceptive control has been associated with low back pain (Gill and Callaghan, 1998, Brumagne et al., 2000, O'Sullivan et al., 2003b, Newcomer et al., 2002, Wilson and Granata, 2003). Furthermore it was noted by Feipel et al., (2003) that in healthy subjects, seated postural stabilisation was more difficult in lateral equilibration tests than other tests. In other words, spinal motion in the frontal plane is more difficult to control. Brumagne et al., (2000) state that 'resolution of motor control problems in the lumbosacral spine is currently an important part of exercise therapy for patients with low back pain'. The results of this study may indicate that the balance demands of rowing in a boat stimulate the proprioceptive system (motor control) of the lumbar spine better than rowing on an ergometer and thus offers some protection from injury.

An observation of this present study was that frontal plane angular displacement increased over the course of the trial on the ergometer but not on the boat. Taimela et al., (1999) found that fatigue had an effect on the ability to sense a change in lumbar position. The fact that the rowers in this study may be starting to fatigue by the end of the trial may explain the change in angular displacement on the ergometer; in the boat an increase in 'wobble' of the boat would feed back this increased movement to the rower who would correct lumbar spine position to 'sit' the boat steady. Fatigue was associated with a change in spinal kinematics in previous studies of rowers (Bull and McGregor, 2000, Mackenzie et al., 2008, McGregor et al., 2005), (Caldwell et al., 2003, Holt et al., 2003, Mackenzie et al., 2008) although all these studies analysed sagittal plane motion only. Again as the finding in this study was not of statistical significance, further work on the effect of fatigue on frontal plane angular changes is required on a larger cohort; this may confirm that fatigue affects frontal plane angular change in the same way as the sagittal plane. This study used an exercise protocol which is likely to cause fatigue as the participants were working at 85% of their maximum heart rate for a period of 10 minutes. However, a clearer analysis may be produced with use of a protocol which is specifically selected to cause an incremental rise in fatigue such as a physiological step test.

Nolte (2005) stated that the frontal plane motion in the lumbar spine in a boat 'can lead to extended loads in the lower back which may increase injury risk in this region.' While this study has not quantified how this may lead to injury, it has confirmed that there is considerable movement in this plane and that it may be greater on an ergometer than a boat. Morris et al., (2000) found that peak compressive forces generated at the lumbar spine of the rower (expressed relative to the subjects' body weight), was 4.6 times the

rowers' body weight. A number of risk factors have been cited for low back pain, one of which is loading in specific spinal positions. A number of the studies reviewed in section 1.6.1 found that subjects reached high levels of lumbar sagittal flexion in rowing (McGregor et al., 2002, McGregor et al., 2005, Caldwell et al., 2003, Pollock et al., 2009, Holt et al., 2003). This study found that rowers reach between 34 and 71% of full frontal plane flexion also during the rowing stroke. This combination of frontal and sagittal motion has been found to be a higher predictor of lumbar spine injury than one movement alone; the risk is further increased when these joint movements are combined with the loading described by Morris et al (2000). Many studies have noted such kinematics in industry and have defined them as clear predictors for lumbar spine injury (Hoogendoorn et al., 2000, Marras et al., 1993, Mundt et al., 1993).

Limitations of study

This study selected a sample of convenience which created limited choice as it was necessary that all were very accomplished scullers so that poor technical ability did not alter findings. Ireland is a small rowing nation and this study was completed the year following the Olympic Games after which many of the top Irish scullers retired from the sport. The equipment used in this study was very simple which allowed it to be portable and made it appropriate to take readings in the boat; however, the simplicity meant that it had associated errors. However, the degree of error was very small (0.5 degrees noted in the calibration study) and even when this was considered, a trend was still observed in the findings. The equipment was not calibrated against a gold standard reference such as MRI as this was not available, although the calibration outlined in Appendix C indicated the system's validity. Calibration against MRI would make reference to the data provided by Li et al., (2009) more meaningful. Weather conditions and tidal flow will affect boat rowing and although they were controlled as far as possible, it is not possible to quantify how they would affect results.

3.7 CONCLUSION

This study showed that there was movement in the lumbar spine of rowers in the frontal plane. The frontal plane angular displacement in the lumbar spine differed between the boat and the ergometer; the ergometer was greater by a mean of 1.6° which was not statistically significant. It was also observed that the frontal plane angular displacement increased over the course of the trial in the ergometer, but not the boat although this value

did not reach statistical significance. This study suggests that there are differences between ergometer and boat rowing which may have implication for injury. Further research into lumbar spine frontal plane kinematics is needed to confirm this finding. The effects of fatigue should also be examined to confirm if frontal plane angular displacement increases over a course of a rowing trial as has been previously demonstrated in the sagittal plane.

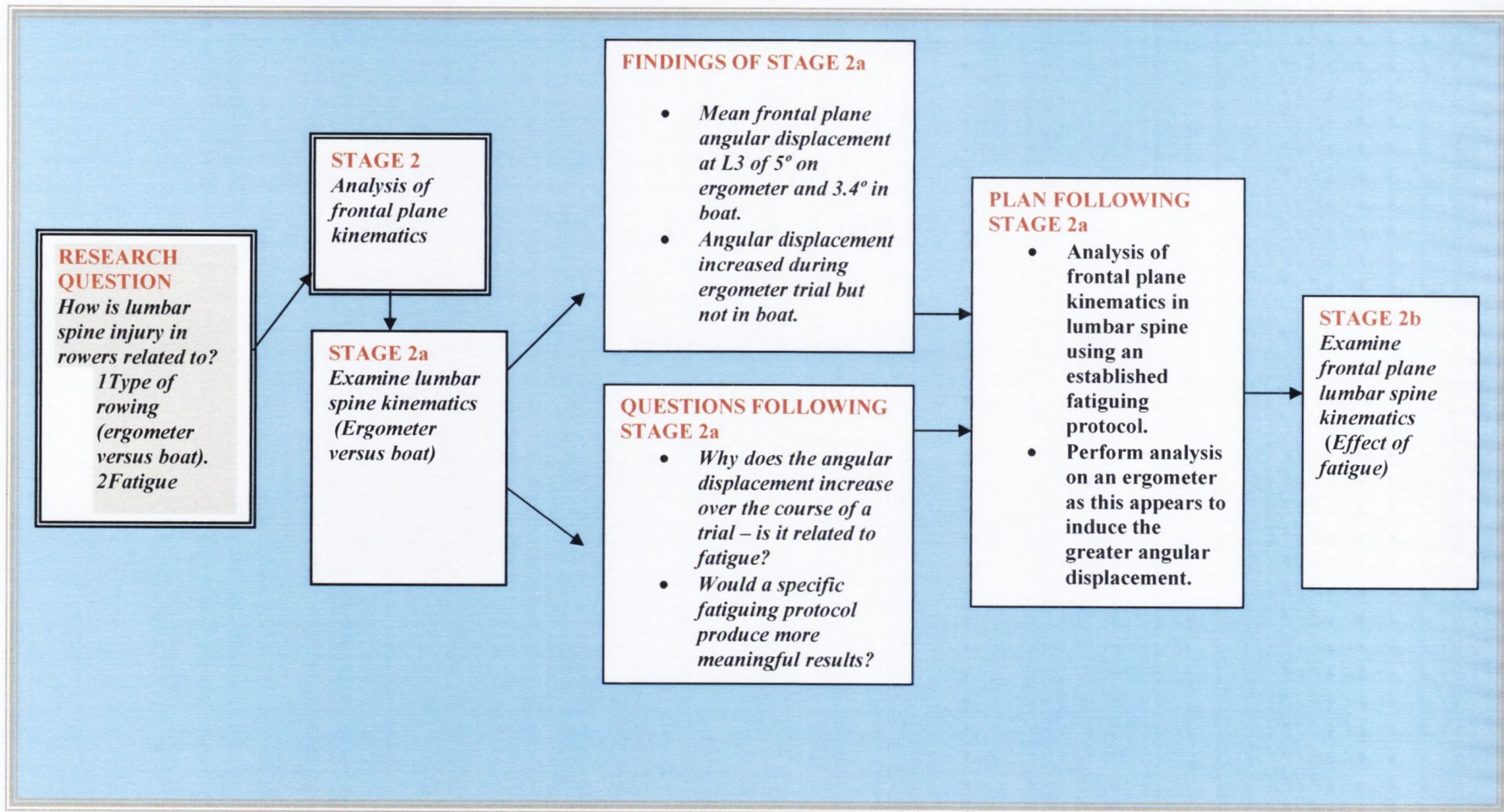


Figure 3.5: Flow chart to show the progression of research following study 2.

CHAPTER 4

STUDY 3

A STUDY TO MEASURE TO EFFECT OF A FATIGUING PROTOCOL ON FRONTAL PLANE ANGULAR CHANGES IN THE LUMBAR SPINE OF ELITE ROWERS: AN EXAMINATION OF ERGOMETER ROWING.

4.1 ABSTRACT.

Objective: To examine the effects of fatigue on changes in angular displacement of the lumbar spine at L3 in the frontal plane, during ergometer rowing.

Methods: The participants in this study were four elite rowers, 3 male, 1 female, mean age 19.8 (1.3) years, mean number of years rowing 5.3 (1.5) years. Lumbar spine kinematics were measured in the frontal plane at L3 during an ergometer rowing trial. The trial comprised a physiological 'step test' on a Concept 2 ergometer. Both work intensity and stroke rate increased incrementally for each stage of the test. Spinal kinematics were measured throughout the rowing trial using a Spectrotilt Inclinometer connected to a Biometrics DataLog system. The inclinometer was attached directly over the spinous process of L3.

Results: As work intensity and stroke rate increased, angular displacement in the frontal plane at L3 increased by between 0.6° and 3.6°. Two of the four subjects demonstrated a statistically significant increase over the course of the test ($P=0.0000215$ and $P=0.000154$). Both of these subjects completed more steps than the others.

Conclusion: High values of lumbar spine frontal plane angular displacement were observed in this study. Angular displacement increased over the course of the test but only significantly by rowers who completed a greater number of steps. Further testing with the inclusion of a physiological test of fatigue may explain the findings more clearly.

4.2 INTRODUCTION.

Study 2 (chapter 3), examined the frontal plane angular changes in the lumbar spine in both ergometer and boat rowing, in a group of rowers. It was expected that the ergometer would cause smaller movement in the frontal plane as the ergometer was placed on a stable surface (land) and the boat was placed on an unstable surface (water) which allows considerable motion in this plane due the shape of the under surface of the boat. However, study 2 demonstrated that ergometer rowing was actually associated with more frontal plane motion in the lumbar spine than in the boat (a mean maximum of 3.6° in the boat and a mean maximum of 5.4° on the ergometer) which may be one of the factors why ergometer rowing is associated with lumbar spine injury in rowers (section 2.6.4). It was also found in study 2 that the frontal plane angular displacement at L3 increased over the course of the ergometer trial which may have been as a result of fatigue. Previous studies have found that fatigue alters lumbar spine kinematics during ergometer rowing (Bull and McGregor, 2000, McGregor et al., 2005, Caldwell et al., 2003, Holt et al., 2003, Mackenzie et al., 2008). With the onset of fatigue, there is compromise in neuromuscular control (Taimela et al., 1999) which may explain why it is associated with changes in spinal kinematics. Thus as the rower becomes fatigued, there is an increased movement in the frontal plane as neuromuscular control is compromised, leading to less efficient technique.

There is a need for a study to examine how the onset of fatigue changes spinal kinematics in the lumbar spine of rowers. Previous studies have demonstrated changes in sagittal plane kinematics during a fatiguing protocol but none have examined the frontal plane. As study 2 showed that greater lumbar spine angular displacement was observed in ergometer rowing than boat rowing, the ergometer will be examined.

4.3 AIM

The aim of this study was to examine kinematics of lumbar spine in the frontal plane under the conditions of fatigue, during ergometer rowing.

4.4 METHODS.

4.4.1 Participants

The subject group examined in this study were four elite rowers, 3 male, 1 female, mean age 19.8 (1.3) years. The mean weight of the participants was 70.8 (3.3) Kg and mean number of years rowing was 5.3 (1.5) years. All were training and competing as part of the

Commercial Rowing Club Senior Sculling Group. Inclusion criteria were: Over 18 years of age; training and competing at senior (elite) level rowing; training at least 5 times/week; no history of lumbar spine injury in the previous 6 months.

Ethical permission was granted for this study from the Trinity College Faculty of Health Sciences Research Ethics Committee and informed written consent was obtained from all participants. The head sculling coach at Commercial Rowing Club, Dublin was contacted and asked to invite rowers to take part in the study

4.4.2 Instrumentation

Analysis of frontal plane angle changes was measured using the instrumentation and method described in section 3.4.2. The sampling rate of the system was 10 Hz with a settling time of 300ms demonstrated in previous calibration in Appendix C. Sampling rate was reduced to 10 Hz from 50Hz (see section 3.4.2) as it was anticipated that this study would take between 24 and 30 minutes per participant compared to 10 minutes in the previous protocol. The Concept 2, Model D ergometer was used as described in section 3.4.2.

4.4.3 Incremental step test.

Each athlete performed an incremental exercise test as described by Mahony et al., (1999) which consisted of steps of increasing workload and rowing rate on the rowing ergometer as outlined below.

The drag factor is a resistance setting on the Concept 2 ergometer which allows the resistance to be adjusted for different body weights. The drag factor is a numerical value for the rate at which the flywheel is decelerating and this number changes with the volume of air that passes through the flywheel housing. Altering the drag factor alters the workload of the machine. The drag factor is displayed on the Concept 2 monitor and is adjusted by opening vents on the flywheel housing. As all participants in this study were lightweight rowers, the drag factor was set at 125 according to Mahony et al. Each rower started at an initial power output of 120W and rowed for 3 minutes at the initial power output at a fixed stroke rate (outlined below in Table 4.1) increasing every 3 minutes in 40 W increments until exhaustion. A rest period of 30 seconds was taken between each incremental increase. Exhaustion was defined as the inability to maintain power output or stroke rate for that step for more than 5 consecutive strokes. The rowers were asked to stop at this point.

| <i>Time</i> | <i>Power output</i> | <i>Stroke rate</i> |
|-------------------------|---------------------|------------------------|
| <i>3mins</i> | <i>120 w</i> | <i>16 - 18 per min</i> |
| <i>3 mins, 30 secs</i> | <i>160 w</i> | <i>18 - 20 per min</i> |
| <i>7mins</i> | <i>200 w</i> | <i>20 - 22 per min</i> |
| <i>10 mins, 30 secs</i> | <i>240 w</i> | <i>22 - 24 per min</i> |
| <i>14 mins, 30 secs</i> | <i>280 w</i> | <i>24 - 26 per min</i> |
| <i>17mins, 30 secs</i> | <i>320 w</i> | <i>26 - 28 per min</i> |
| <i>21mins</i> | <i>360 w</i> | <i>28 - 30 per min</i> |
| <i>24mins, 30 secs</i> | <i>400 w</i> | <i>30 - 32 per min</i> |

Table 4.1: Step test protocol.

This method of testing is a standardised protocol which is frequently used in rowing to assess fitness or to examine physiological variables such as lactate response (Beneke, 1995). In this instance it was utilised to analyse kinematic variables under different work loads.

4.4.4 Protocol

Testing was performed on a Concept 2 model D rowing ergometer (Concept Inc., Vermont). Participants had the equipment attached at L3 as described in section 3.4.3. Prior to the test the participant was asked to sit upright on the ergometer seat, with feet on the ground. This position was selected as the neutral position of the lumbar spine; the Spectrotilt inclinometer was set at zero degrees on the DataLog. All angular displacement recordings were made relative to this zero position. Participants were then asked to complete a 5 minute warm up period on the ergometer at a stroke rating of 18/minute and at 'light pressure' i.e. minimal workload according to Mahony et al. Frontal plane angle changes were measured throughout the rowing stroke using the Spectrotilt inclinometer. The Concept 2 ergometer data display monitor (model PM3, Concept Inc., Vermont.) was programmed with the protocol and the rower started the test when they were ready. Recording on the DataLog was started at the same time as the rower started the test.

4.4.5 Data analysis

The Biometrics DataLog recorded frontal plane angle at a rate of 10Hz over the period of the test for each rower. Data was entered into Biometrics software package (Biometrics Ltd Version 3) and was converted to an ASCII file. It was then entered into Microsoft Excel (2003) and was low pass filtered at 1.35Hz (see Appendix C). From this data, a chart was produced for the period of each test demonstrating deviation from neutral to right and left in the frontal plane of the lumbar spine. For each step, the first twenty peaks and the first twenty troughs were selected. The peak to trough value represented the total frontal plane movement. Values for these points were ascertained and entered into a separate worksheet and the total deviation was calculated.

4.4.6 Statistical analysis.

Statistical analysis of the data was performed using SPSS v15. Differences between the twenty values for each step were examined using a single factor ANOVA. The statistical threshold was set at $P < 0.05$.

4.5 RESULTS

All subjects completed the test with incremental rises in frontal plane angular displacement. An average of 5.75 (0.96) steps was completed. The chart for subject 1 is shown in Figure 4.1 and those for other participants may be viewed in Appendix F.

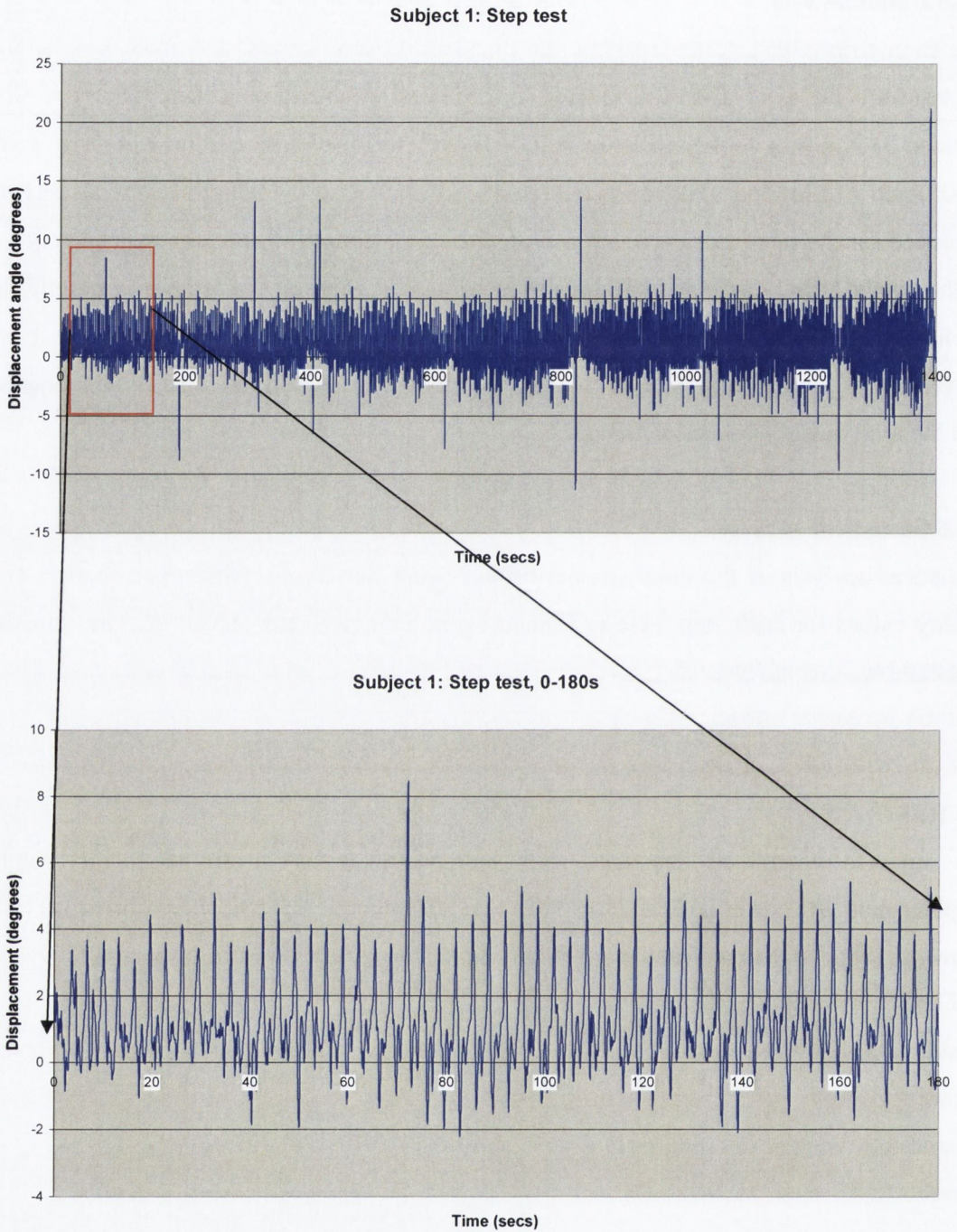


Figure 4.1: Step test chart for subject 1 showing frontal plane angular displacement at L3 over whole test (above) and magnified for step 1 (0-180s) below.

The mean frontal plane angular displacement at L3 for each step was calculated for each subject and is shown in Table 4.2 along with ANOVA results of analysis of significance in angular displacement.

| Subject | Mean angle step 1 (degrees) | Mean angle step 2 (degrees) | Mean angle step 3 (degrees) | Mean angle step 4 (degrees) | Mean angle step 5 (degrees) | Mean angle step 6 (degrees) | Mean angle step 7 (degrees) | ANOVA P value |
|---------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|---------------|
| 1 | 4.3 | 6 | 5.4 | 7 | 6.3 | 6.5 | 7.7 | 0.00002 |
| 2 | 6.9 | 6.8 | 7 | 7.8 | 7.9 | 10.5 | | 0.000154 |
| 3 | 5.1 | 4.3 | 4.9 | 4.6 | 5.3 | | | 0.0595918 |
| 4 | 6.6 | 6.5 | 6.7 | 6.5 | 7.2 | | | 0.213552 |
| Mean | 5.7 | 5.9 | 6 | 6.5 | 6.7 | 8.5 | 7.7 | |
| SD | 1.2 | 1.1 | 1 | 1.4 | 1.1 | 2.8 | | |

Table 4.2: Mean angular displacement at L3 in the frontal plane for the four study subjects.

The increase in mean frontal plane angular displacement was 3.4° (subject 1), 3.6° (subject 2), 0.2° (subject 3) and 0.6° (subject 4). The mean increase in angular displacement was 2° (all steps) or 1° for the 5 steps that were completed by all subjects.

Mean angular deviation of the lumbar spine during each step for each subject is shown in Figure 4.2.

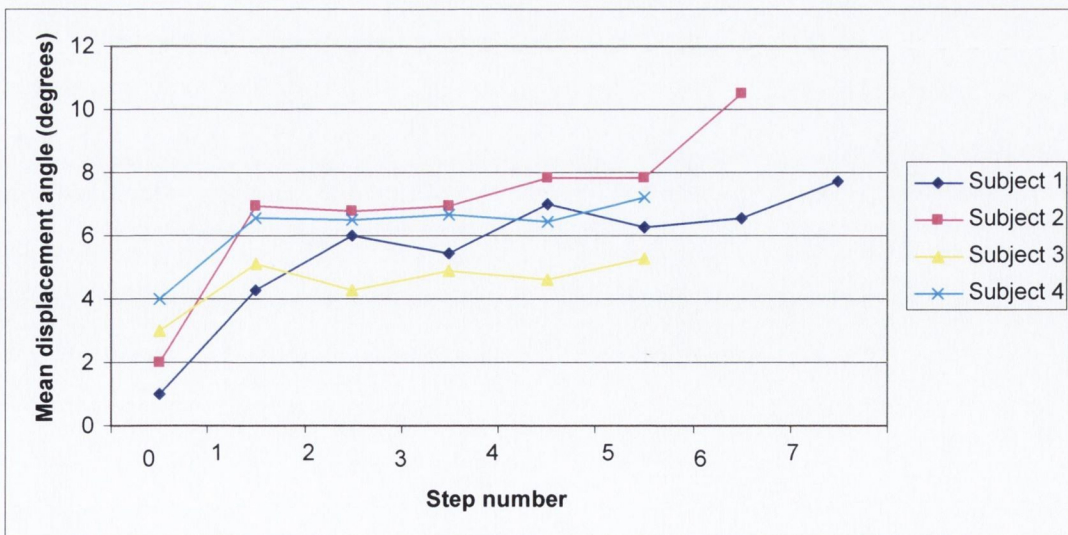


Figure 4.2: Mean angular displacements in the frontal plane at L3 during the stages of the step test; results of the four study participants.

All subjects showed an increase in frontal plane displacement at L3 from the neutral position as the test proceeded with the maximum displacement seen at the last step immediately prior to exhaustion. Two subjects demonstrated statistically significant change, these two subjects completing the greatest number of steps.

4.6 DISCUSSION

This study has confirmed the findings of study 2 that there is frontal plane movement in the lumbar spine of rowers during ergometer rowing. The mean angular displacements (averaged over the whole test) at L3 for the subjects during the test was 6.2° (subject 1), 7.8° (subject 2), 4.8° (subject 3) and 6.7° (subject 4). The angular displacement represents the full frontal plane motion at L3 and is therefore a combination of left and right side flexion. To estimate the single side flexion (either to left or right) the value may be divided by two. Thus the single side flexion values may be estimated as 3.1° (subject 1), 3.9° (subject 2), 2.4° (subject 3) and 3.4° (subject 4). These values correlate closely to the maximum frontal plane range noted for lateral bending at L2/3 (2.9° (2.4)) and L3/4 (3.4° (2.1)) by Li et al., (2009), although the reasons why this should only be judged as a reference point has been discussed previously. The rowers in this study demonstrated large movements in the frontal plane at L3 and the possible implications of this for injury have already been discussed in section 3.6.

This study aimed to examine the effect of fatigue on frontal plane angular changes in the lumbar spine. All subjects showed an incremental increase in angular displacement over the course of the step test. A physiological step test is designed to test an athlete to the point of exhaustion, which is due to fatigue. Fatigue is complicated to define without measuring a number of physiological variables such as lactate response. This study allowed the subjects to exercise to the point of volitional exhaustion which may not necessarily be defined as fatigue. However, psychology plays an important part when testing to the point of exhaustion, particularly as each subject was allowed to choose when to stop, as this may simply be a reflection of their individual tolerance for discomfort. Two subjects, who demonstrated a statistically significant increase in angular displacement over the course of the test, were those who completed the greatest number of steps. It could be that these two individuals had the psychological capacity to 'push themselves harder' and had reached a point of true fatigue in comparison to the others. The Oxford Medical Dictionary (1997) defines fatigue as 'mental or physical tiredness following prolonged or intense activity'. The terms fatigue and exhaustion are clearly ambiguous and to be clear

that the type of fatigue measured in this case is a reflection of the rower's inability to continue due to multi organ response. Measure of a physiological parameter such as blood lactate accumulation throughout the test would provide ancillary data. This is supported by another definition of fatigue as 'fatigue due to the waste products of metabolism accumulating in the muscles faster than they can be removed by the venous blood' (1997).

Section 3.6 discussed why lumbar spine kinematics may change over the course of a fatiguing protocol. This has previously been noted in the sagittal plane and a number of studies (Bull and McGregor, 2000, Mackenzie et al., 2008, McGregor et al., 2005, Caldwell et al., 2003, Holt et al., 2003, Mackenzie et al., 2008). McGregor et al (2005) demonstrated changes in lumbopelvic kinematics in the rower in association with fatigue. This study found that the same response was seen in the frontal plane but was only statistically significant in rowers who completed a higher number of steps.

The fact that the greatest changes are seen in all individuals at the last step i.e. the point immediately prior the time when they are unable to continue, suggests that fatigue may play a role in controlling lumbar equilibrium which is supported by previous studies (Taimela et al., 1999). Fulton et al., (2002) demonstrated that there was a fatigue induced change in corticospinal drive to back muscles in elite rowers. This indicates that changes in angular displacement in this study may be a result of fatigue both at local and corticospinal levels. Lumbar spine angular displacement in the rower may increase as the step test progresses because of differing rates of fatigue in muscle groups lateral to the spine. Parkin et al., (2001) demonstrated that oarsmen have asymmetries in the strength of their back and leg muscles. Thus, if one group is fatiguing more rapidly, there will be differing responses laterally to the spine which will cause increased motion in the frontal plane.

Limitations

There are a number of limitations to this study which must be considered. The two subjects who completed the greater number of steps demonstrated the only statistically significant angular changes. It is not possible to quantify if this is because of psychological differences as there were no other measures to indicate that the rower had reached the point of exhaustion. The angle changes demonstrated in this study may not only be as a result of fatigue but may also be caused by an increased stroke rating at each increase in power output. Further studies should also examine the effect of stroke rating on angular

displacement. As in study 2, a small group of athletes were accessed which was a reflection of the inclusion criteria; the number of elite scullers who were available at this time in Ireland was very small. The mixed gender in this study may have influenced results due to differences between the proportions of the male and female pelvis and lumbar anatomy. Lack of availability of participants necessitated inclusion of a female in the study cohort.

4.7 CONCLUSION

This study has demonstrated that ergometer rowing is associated with high degrees of angular displacement in the frontal plane in the lumbar spine. While all subjects showed an increase in angular displacement over the course of a step test, only two subjects produced a statistically significant result. These two subjects completed a greater number of steps in the tests although it is not possible to quantify if these subjects experienced different levels of fatigue compared to the others. This study may produce clearer conclusions if it were repeated on a larger cohort with the measure of a physiological parameter such as blood lactate to confirm if the participant is exhausted.

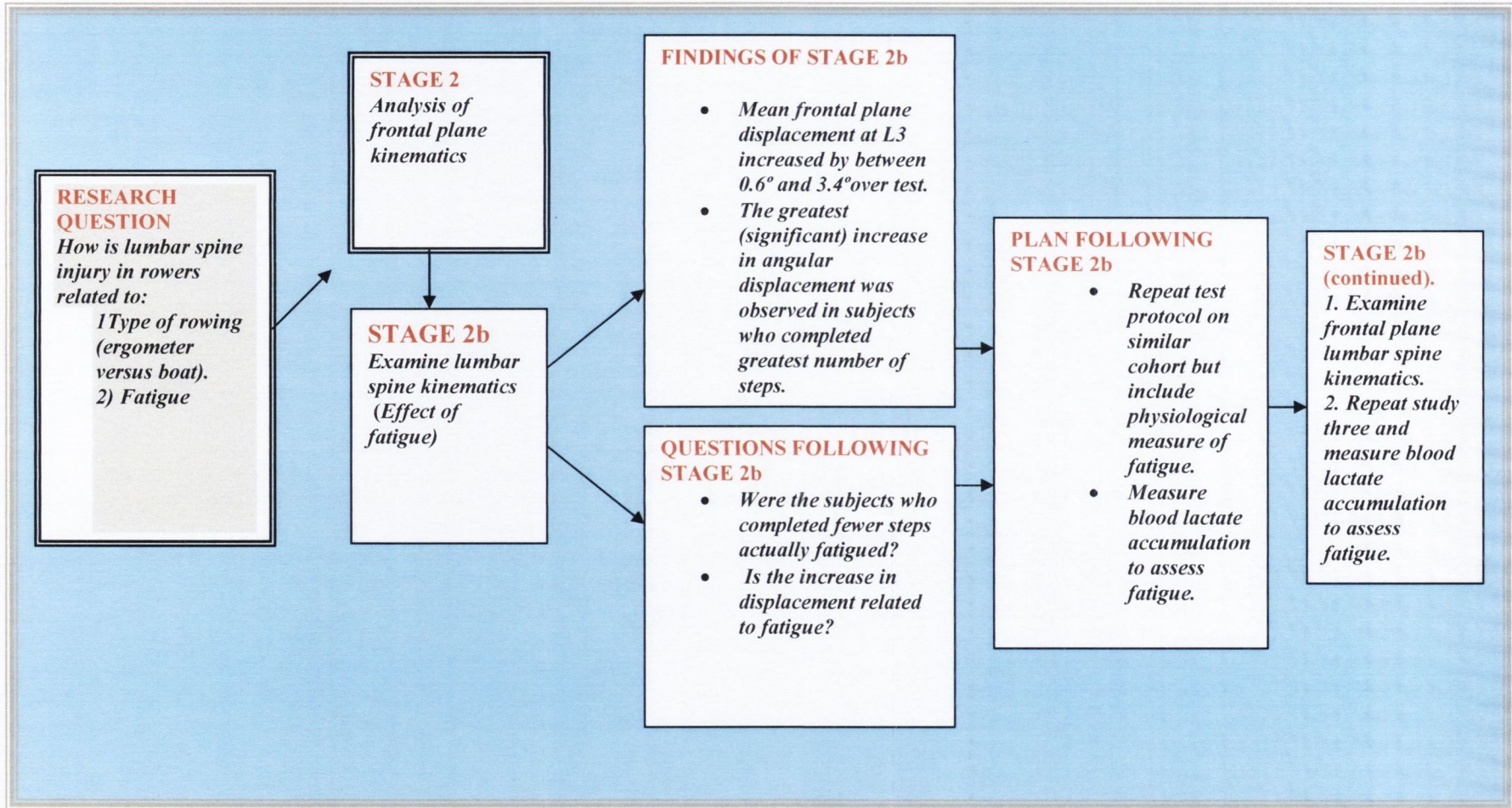


Figure 4.3: Flow chart to show the progression of research following study 3.

CHAPTER 5

STUDY 4

A STUDY TO MEASURE THE EFFECT OF FATIGUE ON FRONTAL PLANE ANGULAR CHANGES IN THE LUMBAR SPINE OF ELITE ROWERS: AN EXAMINATION OF ERGOMETER ROWING.

5.1 ABSTRACT.

Objective: To examine the effects of fatigue (measured by changes in blood lactate accumulation) on changes in angular displacement of the lumbar spine at L3 in the frontal plane during ergometer rowing.

Methods: Participants in this study were twelve elite male rowers, mean age 23.17 (5.15) years, mean weight 79.13 (4.99) Kg. Lumbar spine angular kinematics were measured in the frontal plane at L3 during an ergometer rowing trial. The trial comprised a physiological 'step test' on a Concept 2 ergometer. Both work intensity and stroke rate increased incrementally for each stage of the test. Spinal kinematics were measured continually throughout the rowing trial using a Spectrotilt Inclinometer connected to a Biometrics DataLog system. The inclinometer was attached directly over the spinous process of L3. Blood lactate was sampled at 3 minute intervals throughout the step test using a portable lactate analyser.

Results: It was found that there was a significant increase in frontal plane angular displacement between the first and last stage of the test (mean increase = 4.1° (1.94), 95% CI, 2.9 to 5.3° , $t = 7.36$, $P=0.000014$). While the incremental rise in angular displacement was associated with an incremental rise in blood lactate, regression analysis confirmed that only stroke rate was a significant predictor for increasing angular displacement.

Conclusion: This study has demonstrated that there is a statistically significant increase in frontal plane angular displacement at L3 over the course of an incremental exercise test although it cannot be confirmed if this is as a result of fatigue. The high values of angular displacement reached by the participants in this study confirm that there is considerable motion in this plane (between 4.7° and 8.8°) during rowing and should be considered as a factor for injury. Further investigation is required to assess if the same effect is observed in the sagittal plane.

5.2 INTRODUCTION.

Study 3 (chapter 4) examined the frontal plane angular changes in the lumbar spine during ergometer rowing. It was shown that there was considerable movement in the frontal plane in the lumbar spine and that the range of movement or angular displacement increased as the subject became fatigued. The term fatigue was discussed to have a number of meanings which has popularised the use of the term 'exhaustion' by exercise physiologists. Exhaustion is defined by the Oxford Dictionary as 'a total loss of strength' (Marino et al., 2009). This is clearly inappropriate as the participants in the study were able to continue rowing, but were unable to row within set power and stroke rating parameters. A more appropriate definition of fatigue in the case of rowing is given by Wilmore et al., (2008) as '...the inability to maintain the required power output to continue muscular work at a given intensity'. Study 3 found that the subjects who completed the greatest number of steps during the incremental test were those who demonstrated a statistically significant increase in lumbar spine angular displacement in the frontal plane. As the subjects in study 3 completed the test to the point of 'volitional exhaustion' it was not possible to define if those subjects who did not show a statistically significant increase were truly fatigued or exhausted.

Traditionally, lactic acid or blood lactate concentration was thought to be a cause of fatigue as it is a by-product of anaerobic glycolysis. While it is now recognised that it is not a direct cause of fatigue, accumulation of blood lactate is an indicator of fatigue. The production of blood lactate (along with H^+) during exercise such as rowing is associated with a decrease in muscle tissue pH, despite buffering by the cells and body fluids and this decrease in muscle pH is seen as a limit to continuing exercise (Wilmore et al., 2008). The use of blood lactate concentration (BLa) is popular as a parameter to assess endurance capacity as well as for classifying work rate during exercise and 'is one of the most important means in the diagnosis of endurance performance in sports practice' (Faude et al., 2009). During incremental exercise testing, an exponential rise in BLa can be observed (Faude et al., 2009) although a critical point known as the lactate threshold is reached. The lactate threshold is 'the point during exercise of increasing intensity where lactate clearance is no longer able to keep up with lactate production' (Wilmore et al., 2008). The term lactate threshold is frequently used interchangeably with the term 'onset of blood lactate accumulation' (OBLA) which is a point at which there is a sharp rise in blood lactate accumulation from a relatively steady incline previously. This point is set at 4 mmol per whole litre of blood (McCardle et al., 2010). Thus, measurement of blood lactate

accumulation during incremental exercise is a useful adjunct to confirm that the subject is exhausted.

The justification for this study was that study 3 (chapter 4) showed that rowers show considerable angular displacement in the frontal plane at L3 during incremental exercise tests but also appear to increase this movement as they fatigue. However, there was no specific measure of fatigue in the test protocol, so it could not be confirmed if the participants had reached this state. This study examined the same test on a larger cohort with the measurement of blood lactate accumulation as an indicator of fatigue.

Incremental exercise is associated with a gradual rise in work rate; in the case of rowing this is stroke rate. It is not clear if it is either fatigue or stroke rate which causes an increase in lumbar spine angular displacement. This study also aimed to examine the effect of increasing stroke rate on lumbar spine angular displacement.

5.3 AIM

The aim of this study was to examine the effects of fatigue (measured by blood lactate accumulation) and stroke rate on changes in angular displacement of the lumbar spine at L3 in the frontal plane, during ergometer rowing.

5.4 METHODS.

5.4.1 Participants

Twelve elite rowers, all male, mean age 23.17 (5.15) years, mean weight 79.13 (4.99) Kg were recruited for this study. Inclusion criteria were: over 18 years of age; training and competing at senior (elite) level rowing; training at least 5 times/week; no history of lumbar spine injury in the previous 6 months. Ethical permission was granted for this study from the Trinity College Faculty of Health Sciences Research Ethics Committee and informed written consent was obtained from all participants. The head coach at the five rowing clubs in Dublin was contacted and asked to invite rowers to take part in the study.

5.4.2 Instrumentation

Frontal plane angle changes were measured using the instrumentation and method described in section 3.4.2. The sampling rate of the system was 10 Hz with a settling time of 300ms demonstrated in previous calibration in section 3.4.2 and Appendix C. Data was sampled at 10 Hz to allow for the quantity of data from a test of at least 20 minutes to be sampled. The Concept 2, Model D ergometer was used as described in section 3.4.2.

5.4.3 Incremental step test and blood lactate concentration analysis.

The incremental exercise test as described in section 4.4.3 was the protocol used in this study. Blood lactate was sampled during each 30 second rest period using a Lactate Pro (KDK Corporation, Kyoto, Akray factory inc. Japan) which is a portable, hand held, whole blood, lactate analyser (Figure 5.1). The Lactate Pro has a measuring range of 0.8-23.3 mmol/litre of whole blood and measures blood in samples of 5 μ l. A reagent fills by capillary action directly from the earlobe and lactate in the sample reacts with potassium ferricyanide and lactate oxidase to form potassium ferrocyanide and pyruvate releasing electrons and creating a current. This current is measured amperometrically and is directly proportional to the lactate concentration of the blood sample. The Lactate Pro is supplied with a check strip to confirm that it is working correctly and a calibration strip indicates its accuracy (Pyne et al., 2000) The Lactate Pro has been shown to be accurate and reliable in studies which have measured it against other laboratory based, gold standard lactate analysis equipment (Pyne et al., 2000, Baldari et al., 2009). Correlation between the Lactate Pro and the laboratory based, ABL 700 Series Acid-Base analyser, YSI 2300 was $r = 0.99$ and correlation between two Lactate Pro analysers on the same sample ($n = 96$) was $r = 0.99$ (Pyne et al., 2000).



Figure 5.1: The Lactate Pro blood lactate analyser

(www.lactatepro.com)

5.4.4 Protocol

Testing was performed on a Concept 2 model D rowing ergometer (Concept Inc., Vermont). Participants had the equipment attached at L3 and set at zero degrees as described in section 3.4.3. Participants completed the protocol as outlined in section 4.4.4. After the warm up period and following calibration of the Lactate Pro against the test strip, the right earlobe of the rower was punctured using a small surgical lancet and aseptic technique. The calibration strip was applied to the drop of blood and placed in the Lactate Pro for analysis. Blood was sampled from the same site throughout the test at the

beginning of the 30 second rest period between each step of the test. Heart rate was measured throughout the test using short range radio telemetry (Polar Electro, Kempele, Finland).

5.4.5 Data analysis

Data was analysed as in section 4.4.5. On this occasion, all peaks and troughs of each step of the test were analysed for each participant. Full angular displacement constituted the frontal plane displacement from left to right and was calculated by subtracting the trough from the peak value. For each subject, the mean angular displacement for each step was calculated.

5.4.6 Statistical analysis.

Statistical analysis of the data was performed using SPSS v15. The mean frontal plane angular displacement at L3 during the first step of the test was compared to the last step of the test for all participants using a paired t-test. The statistical threshold was set at $P < 0.05$. A linear regression was performed to analyse the relationship between blood lactate values and frontal plane angular displacement.

5.5 RESULTS

All participants completed seven steps of the incremental test. A chart was created for each participant for the whole test and then for each step to allow reading of the data (see Appendix G). Figure 5.2 shows a typical chart for a participant with the first step of the test (0-180 seconds) magnified for clarity.

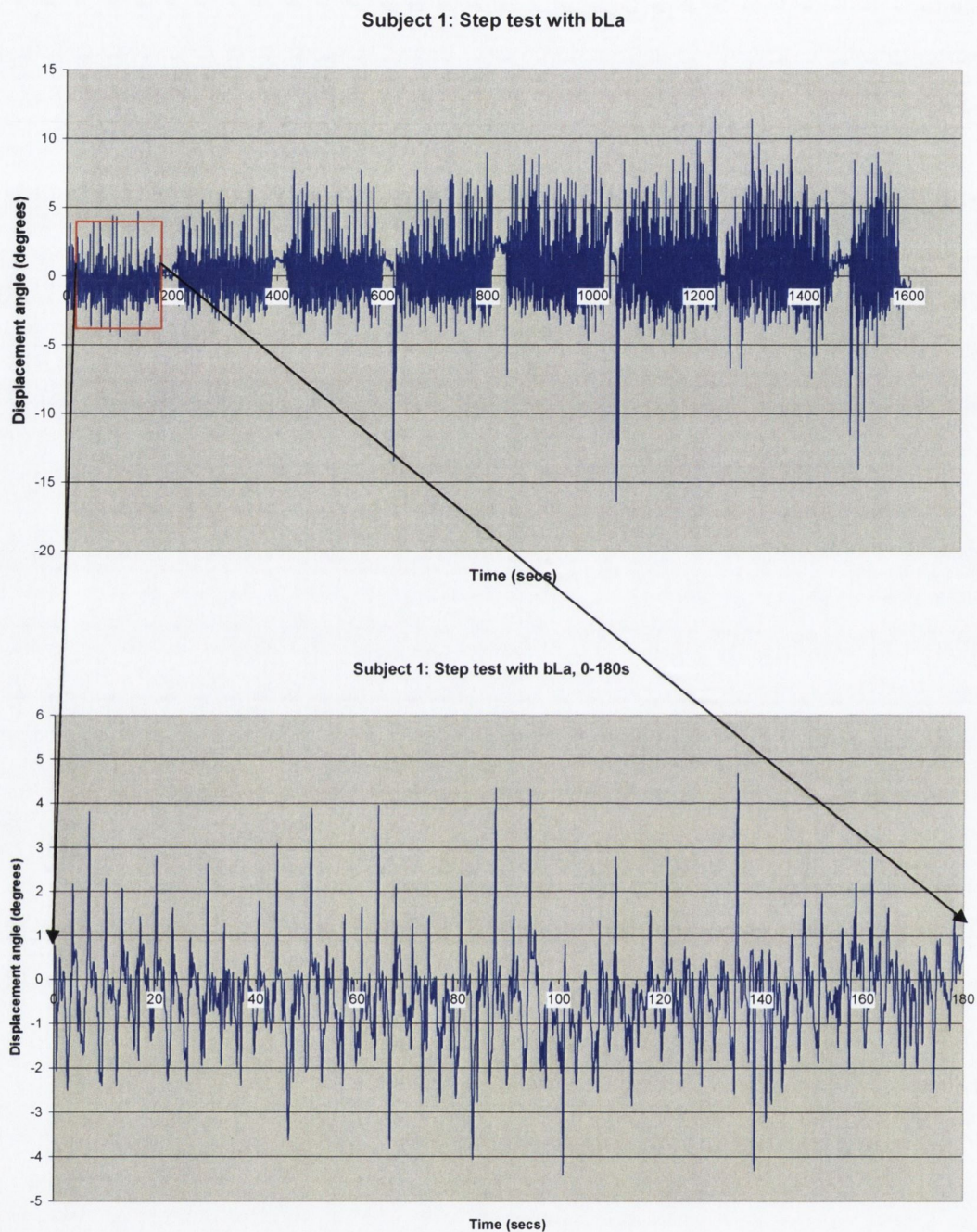


Figure 5.2: Frontal plane angular displacement over the 7 steps of the full test (above) with test stage 1 (0-180 seconds) magnified (below).

The mean frontal plane angular displacement at L3 was calculated for the 12 participants and the mean value of their results for each time period (3 minutes) are shown in Table 5.1.

| Time (secs) | 0-180s | 210-390s | 420-600s | 630-810s | 840-1020s | 1050-1230s | 1260-1440s |
|------------------------------------|------------|------------|------------|------------|------------|------------|------------|
| Subject | | | | | | | |
| 1 | 3.9 | 4.8 | 5.6 | 6.0 | 6.7 | 7.4 | 7.3 |
| 2 | 3.4 | 4.0 | 3.9 | 4.5 | 4.5 | 4.5 | 5.4 |
| 3 | 6.9 | 7.1 | 7.7 | 7.4 | 7.6 | 7.5 | 7.4 |
| 4 | 4.5 | 4.9 | 5.1 | 5.3 | 6.7 | 8.5 | 11.7 |
| 5 | 3.0 | 3.6 | 2.9 | 3.0 | 3.7 | 4.9 | 9.4 |
| 6 | 5.1 | 5.8 | 6.6 | 7.6 | 8.1 | 8.7 | 9.4 |
| 7 | 7.1 | 7.3 | 7.8 | 8.6 | 9.5 | 10.1 | 11.7 |
| 8 | 6.0 | 6.3 | 6.8 | 7.0 | 7.4 | 8.5 | 9.0 |
| 9 | 4.7 | 5.5 | 6.2 | 7.1 | 7.4 | 8.5 | 8.8 |
| 10 | 3.0 | 2.9 | 3.1 | 2.9 | 3.5 | 4.1 | 9.3 |
| 11 | 3.4 | 3.7 | 3.9 | 4.3 | 4.2 | 4.9 | 8.2 |
| 12 | 5.5 | 4.7 | 5.3 | 5.8 | 6.7 | 6.1 | 8.3 |
| Mean displacement (degrees) | 4.6 | 5.2 | 5.5 | 5.8 | 6.4 | 7.1 | 8.7 |
| SD | 1.4 | 1.2 | 1.6 | 1.7 | 1.6 | 1.7 | 2.1 |
| SE | 0.4 | 0.3 | 0.5 | 0.5 | 0.5 | 0.5 | 0.6 |
| 95% Lower CI | 3.8 | 4.4 | 4.4 | 4.7 | 5.4 | 6.0 | 7.3 |
| 95% Upper CI | 5.5 | 6.0 | 6.5 | 6.9 | 7.5 | 8.2 | 10.0 |

Table 5.1: Mean frontal plane angular displacement at L3 over the steps of the test.

The mean values of blood lactate concentration were calculated for all subjects and are shown in table 5.2

| Time (seconds) | 0-180s | 210-390s | 420-600s | 630-810s | 840-1020s | 1050-1230s | 1260-1440s |
|------------------------------------|--------|----------|----------|----------|-----------|------------|------------|
| Mean blood lactate (mmol/l) | 1.2 | 1.2 | 1.6 | 2.4 | 3.7 | 5.9 | 9.0 |
| SD | 0.2 | 0.2 | 0.4 | 0.7 | 1.3 | 1.6 | 2.1 |
| SE | 0.1 | 0.1 | 0.1 | 0.2 | 0.4 | 0.5 | 0.6 |
| 95% CI (lower) | 1.1 | 1.1 | 1.4 | 2.0 | 2.9 | 4.9 | 7.6 |
| 95% CI (upper) | 1.3 | 1.3 | 1.9 | 2.9 | 4.5 | 7.0 | 10.4 |

Table 5.2: Mean blood lactate concentration over the steps of the test (N = 12).

Figure 5.3 shows the increase in mean frontal plane spinal displacement over the time periods of the test.

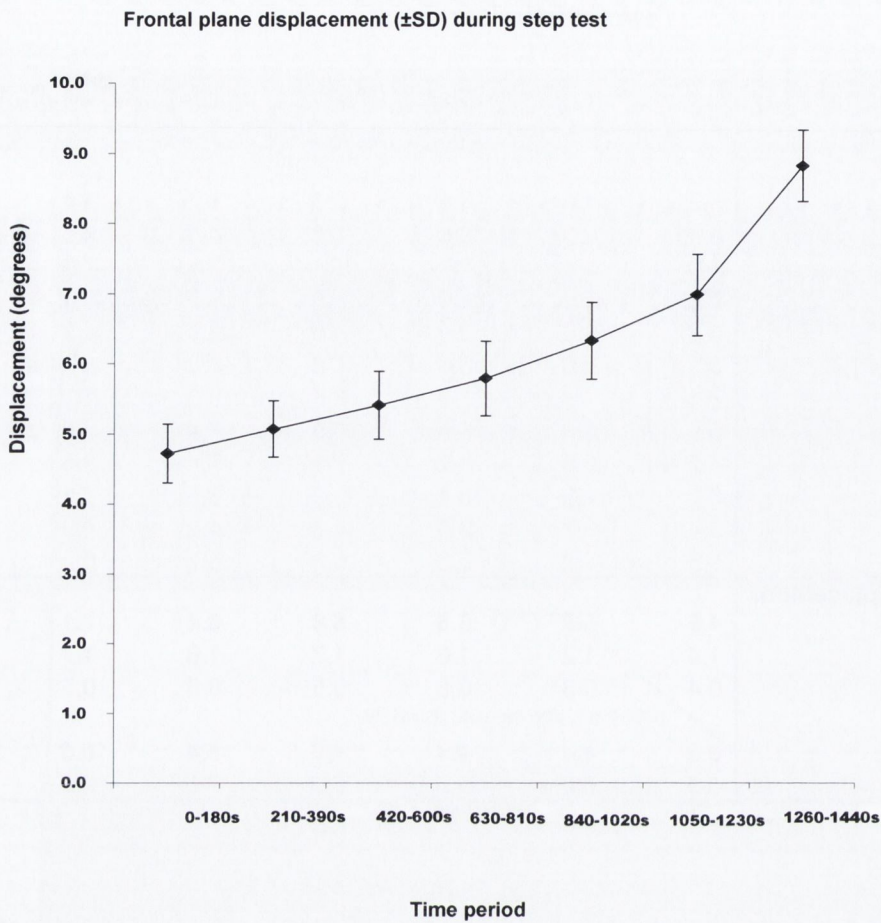


Figure 5.3: Mean Frontal plane angular displacement (\pm SD) during the time periods of the test.

A comparison of the results of the mean frontal plane angular displacement at L3 was made between the first step of the test (0-180s) and the last step of the test (1260-1440s) for all participants. The mean results are shown in Table 5.3.

| Subject | 0-180s (step 1) | 1260-1440s (step 7) | Change (degrees) | % change (%) |
|----------------|------------------------|----------------------------|-------------------------|---------------------|
| 1 | 3.9 | 7.3 | + 3.4 | 87 |
| 2 | 3.4 | 5.4 | + 2 | 59 |
| 3 | 6.9 | 7.4 | + 0.5 | 7 |
| 4 | 4.5 | 11.7 | + 7.2 | 160 |
| 5 | 3.0 | 9.4 | + 6.4 | 213 |
| 6 | 5.1 | 9.4 | + 4.3 | 84 |
| 7 | 7.1 | 11.7 | + 4.6 | 65 |
| 8 | 6.0 | 9.0 | + 3 | 50 |
| 9 | 4.7 | 8.8 | + 4.1 | 87 |
| 10 | 3.0 | 9.3 | + 6.3 | 210 |
| 11 | 3.4 | 8.2 | + 4.8 | 141 |
| 12 | 5.5 | 8.3 | + 2.8 | 51 |

Table 5.3: Mean frontal plane angular displacement at L3 for first and last stages of the test.

A paired t-test was conducted to analyse mean angular displacement between the first stage and last stage of the test. It was found that there was a significant increase in frontal plane angular displacement between the first and last stage (mean increase = 4.1 ° (1.94), 95% CI, 2.9 to 5.3, $t = 7.36$, $P=0.000014$).

The mean results for angular displacement were plotted along with mean blood lactate concentration values for all participants. The result is shown in Figure 5.4.

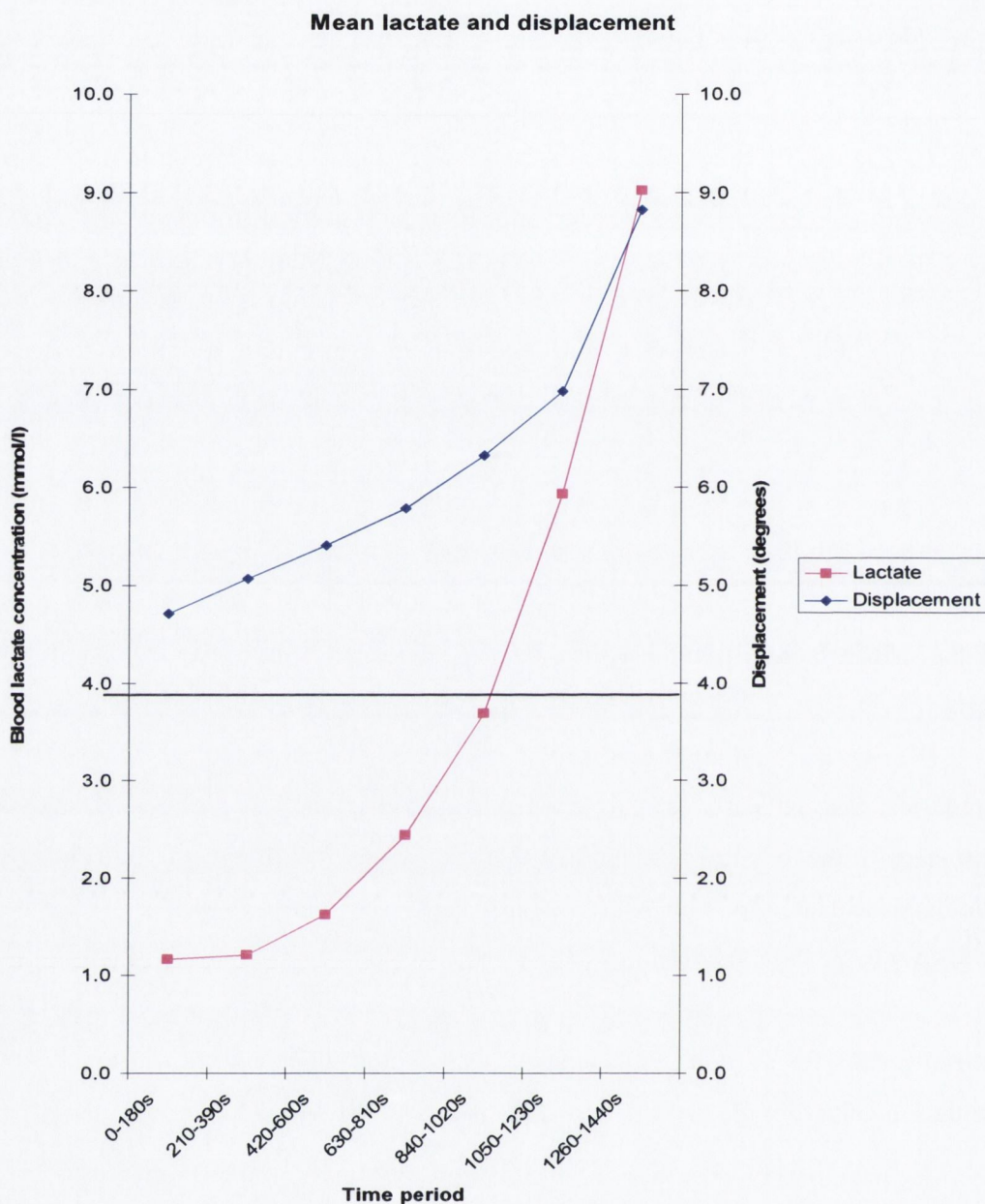


Figure 5.4: Mean blood lactate concentration plotted with mean angular displacement for the time periods of the step test (lactate threshold shown at 4mmol/l).

A linear regression describing the relationship between displacement and lactate levels showed that changes in displacement were significantly associated with changes in lactate (displacement = $4.903 + (0.351 \times \text{lactate score})$), ($P < 0.0001$, $R^2 = 0.24$). A further linear regression using stroke rate as the predictor variable also demonstrated a significant relationship for changes in stroke rate and changes in displacement (displacement = $-0.843 + (0.341 \times \text{stroke rate})$) ($P = 0.0001$, $R^2 = 0.335$). However, when the two predictor

variables were included in a further regression analysis, only stroke rate was a significant predictor of displacement of the spine during the rowing step test ($P=0.001$).

A regression of lactate against displacement in each of the seven time periods showed that lactate levels accounted for between 0.2% and 21.5% of the variation in spinal displacement at any given stage of the step test (Table 5.4).

| <i>Time period</i> | <i>R²</i> |
|--------------------|----------------------|
| 0-180s | 0.20 |
| 210-390s | 0.020 |
| 420-600s | 0.098 |
| 630-810s | 0.183 |
| 840-1020s | 0.215 |
| 1050-1230s | 0.213 |
| 1260-1440s | 0.002 |

Table 5.4: Explained variation in frontal plane angular displacement at L3 from lactate scores during the step test.

5.6 DISCUSSION

This study confirmed that there is considerable motion in the frontal plane at L3 during rowing. Mean angular displacement varied from 4.6° (1.5) during the first step of the test to 8.7° (1.8) at the last step. As described in the previous study, the angular displacement represents the full left to right movement so half the value will approximate single side flexion. Thus it can be estimated that the participants' mean side flexion was between 2° and 4°. These values correlate closely to the maximum frontal plane range noted for lateral bending at L2/3 (2.9° (2.4)) and L3/4 (3.4° (2.1)) in a previous study (Li et al., 2009), although, as discussed previously, this should only be regarded as a reference point due to the disparity between measurement methods.

There was a significant increase in mean frontal plane angular displacement between the first and last step of the test ($P=0.000014$). This has previously been noted in the sagittal plane (Bull and McGregor, 2000, Mackenzie et al., 2008, McGregor et al., 2005) and this study has demonstrated similar changes in the frontal plane. The greatest increase in mean angular displacement was observed between the sixth and seventh (last) stage of the test which corresponded with the sharpest rise in mean blood lactate concentration (see Table 5.1 and 5.2). This suggests that fatigue may contribute to this change. However a regression analysis was not able to confirm that blood lactate concentration was a significant predictor of spinal angular displacement. Table 5.4 showed that lactate levels accounted for between 0.2% and 21.5% of the variation in spinal displacement and that this figure changed in a non-incremental fashion through the test, showing the greatest influence at the fifth and sixth stages of the test, but at only 0.2% in the final stage. The only significant predictor was stroke rate ($P=0.001$) which suggests that it may have been the quicker movement up and down the slide of the ergometer, rather than fatigue, which caused the increased frontal plane motion. Section 4.6 discussed the complex causes of fatigue and for this reason, this result should be interpreted with caution. Blood lactate concentration is a single physiological parameter which may indicate fatigue but is not a single cause. Despite this, blood lactate has been selected as a parameter to measure fatigue in a number of previous studies (Davey et al., 2002, Royal et al., 2006). However, a more recent study (Macedo et al., 2009) concluded that lactate production is not related to performance decrement and is thus a poor measure of fatigue. To provide a clear measure of fatigue, multiple factors need to be considered and there needs to be an understanding that 'fatigue is the result of a complex interaction of multiple peripheral physiological systems and the brain' (Lambert et al., 2005). Furthermore, Weir et al., (2006) argue that

'lactic acid models do not adequately explain fatigue and a variety of peripheral factors, other than lactic acid are known to compromise muscle force and power'. This study shows that increasing stroke rate is associated with increased frontal plane angular displacement at L3, but cannot confirm that it is as a result of fatigue. Further analysis of multiple components of fatigue may give clearer results.

The implications for injury associated with the degree of frontal plane motion observed in this study should be considered. The range of frontal plane motion observed was already at near maximum voluntary range as cited by Li et al., (2009) in the first step but increased to levels much higher than those reported by the same author (see paragraph 1, above). It must also be considered that the high range of this motion is also associated with loading during the rowing stroke. Such motion patterns (i.e. full range lateral lumbar flexion combined with loading) have previously been noted as risk factors for lumbar spine injury in work place studies (Hoogendoorn et al., 2000). This study suggests that high stroke rates, possibly combined with fatigue (although this has not been clearly defined) should be avoided by rowers wishing to avoid lumbar spine injury.

Limitations.

This study used a standard incremental test which increased stroke rate throughout the protocol. A single stroke rate throughout the test may allow more clear analysis of how fatigue affects lumbar spine kinematics. Blood lactate accumulation is a single physiological indicator of the onset of fatigue and measurement of a number of different parameters may provide more clarity.

5.7 CONCLUSION

This study demonstrated a statistically significant increase in frontal plane angular displacement at L3 over the course of an incremental rowing exercise test. While increases in blood lactate concentration were associated with the increase in angular displacement, blood lactate was not found to be a significant predictor of angular displacement but an increase in stroke rate was. The high values of angular displacement reached by the participants in this study confirm that there is considerable motion in this plane during rowing and should be considered as a factor for injury as full range side flexion (frontal plane) combined with lumbar flexion (sagittal plane) with the addition of loading has been observed to be a risk factor for low back pain.

5.8 SUMMARY OF OBJECTIVES FOLLOWING STAGE TWO.

✓ = Completed

X = Not yet completed

- To establish an injury profile and identify predictors for injury in rowers ✓.
- Determine the frontal plane kinematics of the lumbar spine when rowing ✓.
- Compare the frontal plane kinematics of the lumbar spine when rowing in a boat with rowing on an ergometer ✓.
- Compare the sagittal plane kinematics of the lumbar spine when rowing in a boat with rowing on an ergometer X.
- Examine kinematics of lumbar spine in both the frontal ✓ and sagittal X plane under the conditions of fatigue.
- Compare the kinematics of the lumbar spine when rowing in a boat with rowing on an ergometer, under the conditions of fatigue (frontal plane ✓, sagittal plane X).

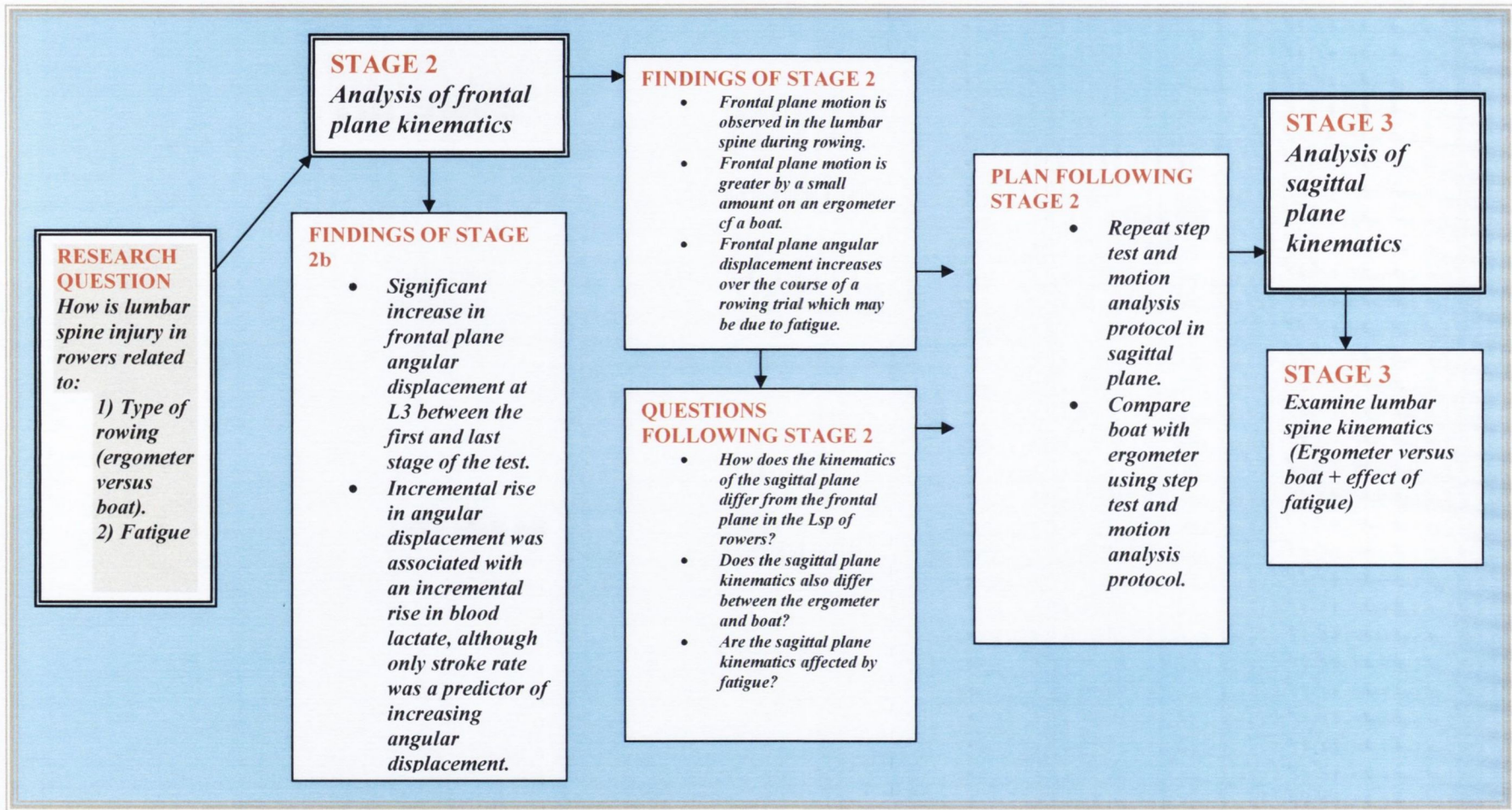


Figure 5.5: Flow chart to show the progression of research following study 4.

CHAPTER 6

STUDY 5

A STUDY TO EXAMINE CHANGES IN KINEMATICS OF SAGITTAL LUMBAR SPINE MOTION IN ROWING DURING A FATIGUING PROTOCOL: A COMPARISON OF ERGOMETER AND BOAT ROWING.

6.1 ABSTRACT

Objective: To examine and compare the sagittal plane kinematics of the lumbar spine in rowers on a rowing ergometer and in a single sculling boat over the course of a fatiguing protocol.

Methods: Participants in this study were nineteen elite rowers, all male, mean age 24.2 (3.7) years, mean weight 82.5 (8.4) kg and height 1.88 (0.05) metres. Lumbar spine kinematics were measured with an electrogoniometer during a physiological 'step test'. The analysis was performed both on an ergometer and in a sculling boat.

Results: Maximum lumbar flexion increased over the course of the test. The increase in lumbar flexion was significantly greater on the ergometer (mean change + 4.4° (0.85)) compared with the boat (mean change + 1.3 ° (1.1)) (mean difference 3.1 °, 95% CI, 0.3 to 5.9, $t = 2.28$, $P=0.035$).

Conclusion: Lumbar spine sagittal flexion increased significantly over the course of an ergometer trial. While lumbar sagittal flexion also increased by a small value during boat rowing, the increase was not statistically significant. This may explain why ergometer rowing poses a greater risk of lumbar spine injury than boat rowing.

6.2: INTRODUCTION

Studies 2, 3 and 4 (chapters 3, 4 and 5), showed that rowers exhibit considerable angular rotation in the frontal plane in their lumbar spine during rowing. All three studies also showed that the angular rotation increased as the rowing trial continued, which may have been due to fatigue. Study one found that the most common injury in rowers was to the lumbar spine and noted that increased time spent ergometer training was significantly associated with risk of lumbar spine injury. Comparison of ergometer and boat kinematics in study two showed that there was greater frontal plane angular displacement in the lumbar spine on the ergometer, compared with a boat. Previous studies have examined kinematics of the lumbar spine on an ergometer but only in the sagittal plane (Holt et al., 2003, Bull and McGregor, 2000, McGregor et al., 2005, Caldwell et al., 2003). The previous studies noted, all examined the effect of a fatiguing protocol and like studies 2, 3 and 4, found that range of spinal motion increased as the trial progressed. The studies completed in this thesis to this point indicate that there are similar lumbar spine kinematics observed in the frontal plane during a rowing protocol to those noted in previous studies in the sagittal plane. The range of frontal plane angular displacement is at maximum voluntary range and the range of motion increases over the course of a fatiguing protocol.

Rowing is an activity which involves cyclical flexion and loading of the lumbar spine which may occur hundreds of times over a training session either on the water or in an ergometer. In addition, rowers will continue a training session to the point of fatigue on a regular basis. Cyclical lumbar flexion, particularly when combined with fatigue, may alter joint mechanics and loading patterns of the lumbar spine, leading to risk of tissue failure and resulting injury (Dolan and Adams, 1998, Caldwell et al., 2003, Parkinson et al., 2004, Holt et al., 2003, Mackenzie et al., 2008).

Studies which have examined lumbar spine sagittal plane kinematics while rowing on an ergometer have demonstrated that rowers achieve high levels of lumbar flexion during the rowing stroke and that these levels increase during the course of a rowing trial (Caldwell et al., 2003, Holt et al., 2003). However, examination of joint kinematics while the rower is in a boat on the water has been limited to video analysis of multiple body segments (Lamb, 1989), so comparison of spinal kinematics has not been possible (Steer et al., 2006).

Thus while this thesis has so far examined the frontal plane angular displacement in the lumbar spine in both the boat and ergometer, there is a need to examine sagittal plane motion (in both the ergometer and the boat) to develop a more comprehensive picture of patterns of activity in the lumbar spine which may contribute to injury. Furthermore, as the studies so far have shown that frontal plane kinematics change as a result of a fatiguing protocol, this should also be examined in the sagittal plane.

6.3 AIM

The primary aim of this study was to examine and compare the sagittal plane kinematics of the lumbar spine in rowers on a rowing ergometer and in a single sculling boat. The second aim of this study is to examine the effect of fatigue on sagittal plane kinematics of the lumbar spine of a rower during training on an ergometer and in a boat.

6.4 METHODS

6.4.1 Participants

Nineteen elite rowers, all male, mean age 24.2 (3.7) years, mean weight 82.5 (8.4) kg and height 1.88 (0.05) metres were recruited for this study. The inclusion criteria were that participants were over the age of 18, should have been rowing at senior level for at least one year and should not have had a lower back injury in the last 6 months. Ethical permission was granted for this study by the Trinity College Faculty of Health Sciences Research Ethics Committee and written consent was obtained from all participants. All members of the senior sculling squads of rowing clubs in Dublin ($N = 35$) were invited to participate in this study on a voluntary basis. The head coach of each club was contacted by e-mail and provided with details regarding the study. Any rower who expressed interest in taking part in the study informed the coach who passed on contact details.

6.4.2 Instrumentation

Lumbar spine range of motion in the sagittal plane was measured using a flexible, twin axis, SG150B electrogoniometer (EGM) (Biometrics Ltd, UK) connected to a DataLog (Biometrics P3X8). A sample rate of 10Hz was selected to allow data of at least 20 minutes duration to be collected. Results were uploaded to a computer using Biometrics

Ltd Version 3 software. The EGM has shown good reliability (Veira and Coury, 2004, Piriyaarasath et al., 2008, Shiratsu and Coury, 2003, Salvia et al., 2006) and validity (Brumagne et al., 1999, Shiratsu and Coury, 2003, Rowe et al., 2001) in previous studies. Before use, the EGM was calibrated against the Baseline Universal Goniometer (Electro Medical Supplies, Wantage, UK). This study is outlined in Appendix H.

The base of the upper electrode was placed over the spinous process of L2 and the top of the lower electrode was placed over the spinous process of L4 to assess the area of the lumbar spine where the greatest degree of sagittal flexion is observed (Bogduk, 2005). First the skin was cleaned with alcohol and sprayed with 'Tuf-Skin' (Cramer, USA) to reduce slippage of the electrodes. The electrodes were placed while the participant was standing, and secured with double sided tape. A mark was made with a black permanent pen at the top and bottom of the electrode, to record if movement of the electrode over the skin occurred during the test due. Once in situ, the EGM was further secured with the use of zinc oxide tape. The DataLog box was placed in a small backpack on the participant's upper back for both the boat and ergometer tests. The participant was asked to stand upright, with feet shoulder width apart, prior to the test. This stance was selected as the neutral position of the lumbar spine and the EGM was set at zero degrees. All angular displacement recordings were made relative to this zero position.

6.4.3 Protocol

The first measurement that was taken was to establish the full, active available range of lumbar flexion in the sagittal plane. The participant was asked to fully flex the lumbar spine by bending forwards to touch their toes, while maintaining the knees in an extended position, and the full angular range of lumbar flexion was recorded. Weight and height were also recorded for each individual. The protocol that was used for testing in both the boat and ergometer was the standard physiological multi stage fitness test or 'step test' described in section 4.4.3. A rest period of 1 minute was taken between each incremental increase. Exhaustion (as a result of increasing fatigue) was defined as the inability to maintain power output or stroke rate for the whole of the step. If the rower was unable to complete 5 consecutive strokes at the required stroke rate and/or power output, they were requested to stop. The first step was rowed at a rate of 18 strokes per minute with subsequent steps increasing to 20, 22, 24, 26, 28 and 30 strokes per minute. Heart rate was measured by short range telemetry (Polar Electro, Finland.). Testing was carried out initially on a Concept 2 model D rowing ergometer (Concept Inc., Vermont.).

The step test was then repeated for each individual in a single sculling boat. All tests were carried out on the same stretch of a river in the same direction to reduce effects of a flowing tide. Wind speed was measured using a Kestrel 1000 (Nielsen Kellerman USA) to ensure that wind speed was less than 10 kph/hr during all tests. As power output cannot be measured in a sculling boat, the test was carried out with the same time intervals and stroke rates as for the first test, but the subjects were asked to increase their power output so that their heart rates reached those levels measured for each step on the ergometer. The heart rates had been recorded for each step on the ergometer and were placed on a waterproof chart on the front deck of the sculling boat for the athlete to refer to during each step. Heart rate, stroke rate and interval time were measured in the boat using a Speedcoach XLI (Nielsen Kellerman USA). Before each test, the EGM was set at zero degrees as described above, peak standing flexion was measured (as above) and the sagittal plane movements of the lumbar spine were continually recorded throughout the test. At the end of each test, position of the pen marks at the top and bottom of the EGM electrodes were assessed to ensure that there had been no slippage during the test.

6.4.4 Data analysis and statistics.

The Biometrics DataLog recorded sagittal plane angle changes over the period of the test for each rower. This data was downloaded into the Biometrics software package and converted into an ASCII file which was exported to Microsoft Excel. A chart was produced for each 3 minute increment of rowing showing a series of peaks and troughs. The peaks represented maximum flexion and the troughs represented minimum flexion of the lumbar spine. Changes in maximum lumbar flexion (mean 'peak maximum' angle), minimum lumbar flexion (mean 'peak minimum' angle), lumbar displacement (distance from maximum flexion to minimum flexion angle) and mean lumbar angle between the first and last steps of the protocol were analysed for each athlete.

Statistical analysis of the data was performed using SPSSv16. Changes in maximum flexion, minimum flexion, displacement and mean lumbar angle between the first and last steps of the protocol were analysed for each athlete, using a paired t-test, as were differences between these changes on the ergometer and in the sculling boat. The first and last steps were chosen for analysis as the test is completed to 'volitional exhaustion' so it can be presumed that the first stage represents a non fatigued state and the final stage represents the peak of fatigue. The statistical threshold was set at $P < 0.05$.

6.5 RESULTS

The mean number of incremental steps completed by each rower was 6.7 (0.7) steps. Lumbar spine sagittal kinematics was significantly different on the ergometer compared with the boat. Excel charts were produced from the converted data output for each test. Figures 6.1 and 6.2 presents the results of subject 1. Figure 6.1 and 6.2 shows 7 incremental steps performed in a boat and on an ergometer with the first step magnified below for clarity. Each block of 7 motion cycles represent the maximum flexion (the peak) and the minimum flexion (the trough) of sagittal plane motion. The first block contains 18 cycles of movement (18 strokes) and the last contains 30 cycles (30 strokes).

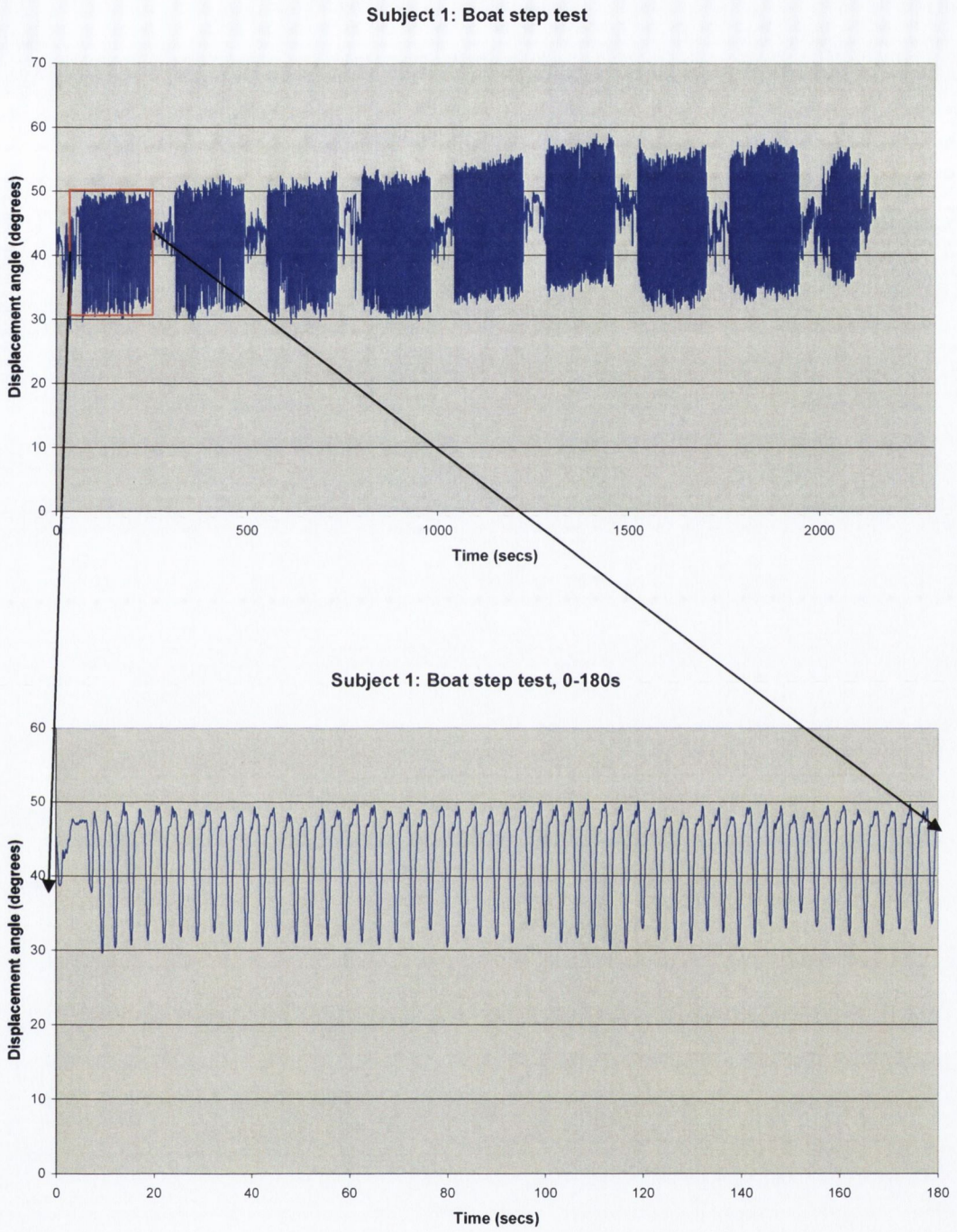
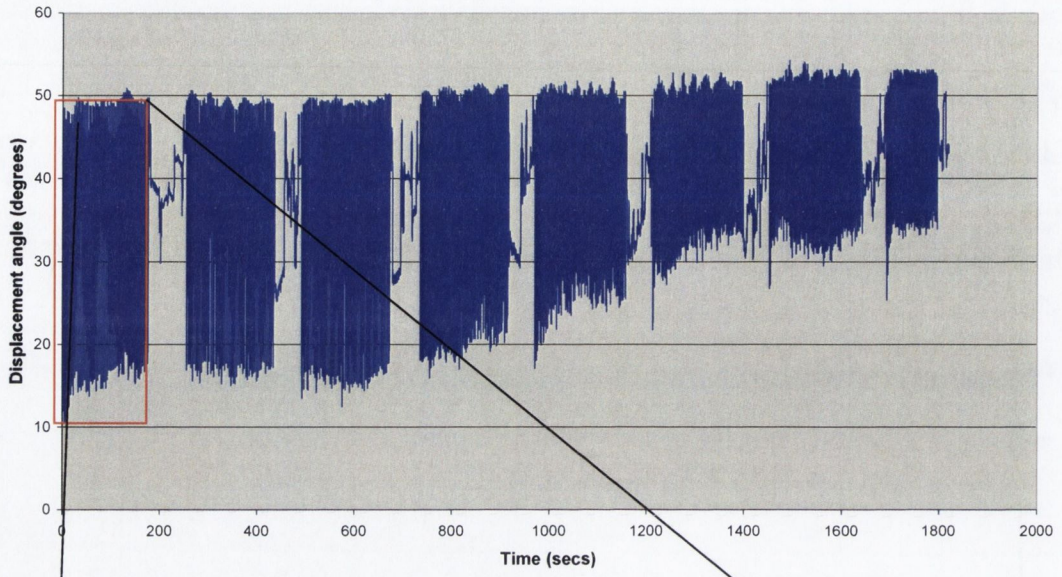


Figure 6.1: Step test in a sculling boat with the first step (0-180s) magnified.

Subject 1: Ergometer step test



Subject 1: Ergometer step test, 0-180s

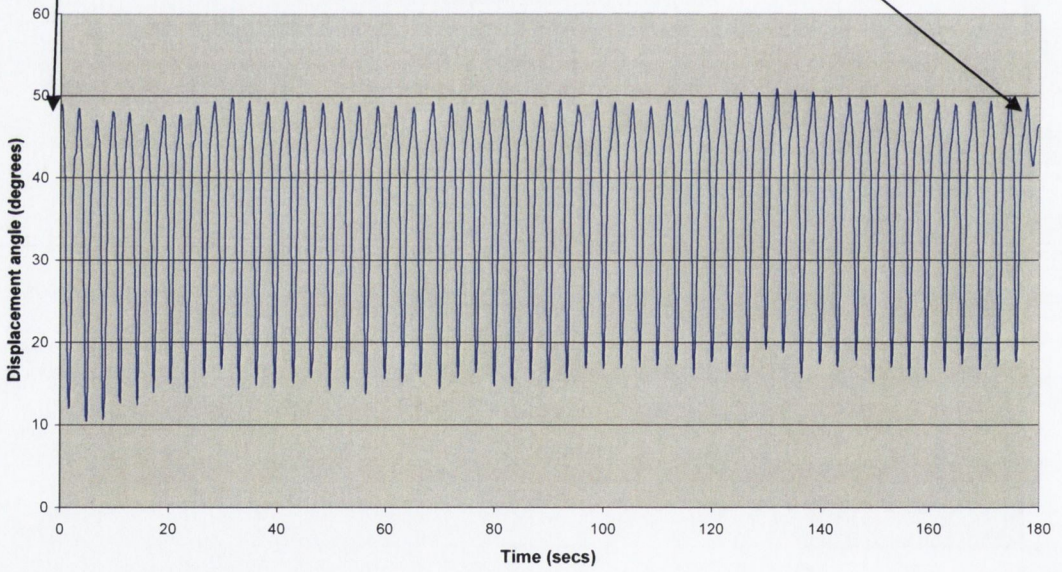


Figure 6.2: Step test on a Concept 2 ergometer with the first cycle magnified.

The charts for all other participants may be seen in Appendix I.

6.5.1 Reliability of the EGM

The degree of error noted in the calibration study was 0.45° (see Appendix H). However, the degree of error is likely to be less in the findings of this study as the mean peak angle recorded was on the ergometer at 54.3° (9.4). The degree of error noted in the calibration study was across all readings up to 90° and was less for readings at the lower end of the scale.

6.5.2 Mean peak flexion angle measured as a percentage of peak flexion in standing.

All participants had their peak standing lumbar flexion (touching toes with knees extended) measured prior to each step test. This peak standing flexion (PSF) was compared to the mean peak flexion (MPF) that the individuals reached at the last stage of the test. On the ergometer, the lumbar flexion angle increased over the course of the trial (mean MPF = 111.3% (15.2), (95% CI, 104.5 to 118.2%) of PSF, pre-test). In the boat the angle also increased by a smaller amount (mean MPF = 104.1% (10), (95% CI, 99.6 to 108.6%) of PSF, pre-test). There was a significant difference between the ergometer and boat findings from the pre-test PSF to the MPF at the last stage of the test ($P=0.01$).

6.5.3 Lumbar spine kinematics on the ergometer

The charts were analysed for the ergometer tests. The mean results for the first 3 minute step and the last 3 minute step were collected and compared. Mean maximum and minimum lumbar angle as well as mean displacement and mean angles were examined. There were significant differences between the first and last step in two of these components on the ergometer; the mean displacement and mean maximum angle. The mean displacement for the first 3 minute step (18.9° (6.1)) was compared to the mean displacement in the last step (23.6° (5.3)). There was a significant increase in displacement angle between the first and last step (mean difference 4.7° , 95% CI, 1.8 to 7.6° , $t = 3.45$, $P=0.0028$). Analysis of mean maximum angle demonstrated a similar increase between the first (49.9° (8.2)) and last step (54.3° (9.4)). This change represented a significant difference (mean difference 4.4° , 95% CI 2.1 to 6.2° , $t = 5.2$, $P=0.001$)

6.5.4 Lumbar spine kinematics in the boat.

A small increase in angular displacement was observed between the first step (17.6° (3.9)) and last step of the test (18.9° (4.3)), but this was not significant (mean difference 1.3° , 95% CI, -0.1 to 2.8° , $t = 1.93$, $P = 0.07$). Mean maximum angle showed a small increase

between the first (50.8° (6.8)) and last step (52.1° (8.5)), but again the difference was not significant (mean difference 1.31°, 95% CI, -0.9 to 3.5 °, $t = -1.26$, $P = 0.223$).

6.5.5 Comparison of lumbar spine sagittal plane kinematics on the ergometer and in the boat.

When the findings of the mean angle changes between the first and last steps in the boat and on the ergometer were compared, a number of significant differences were found. In two measurements, there was a significantly greater increase in angle change between the boat and the ergometer. The mean maximum lumbar angle change between the first and last steps was significantly different between the ergometer (mean change + 4.4° (0.85)) and boat (mean change + 1.3° (1.1)) (mean difference 3.1°, 95% CI, 0.3 to 5.9 °, $t = 2.28$, $P = 0.035$). Similarly, mean angular displacement between the ergometer (mean change + 4.7° (1.3)) and boat (mean change + 1.3° (0.7)) were significantly different (mean difference 3.4 °, 95% CI, 0.4 to 6.4 °, $t = 2.38$, $P = 0.029$). Although the change in mean lumbar spine angle and mean minimum lumbar spine angle were greater on the ergometer compared to the boat, these findings were not significant. Figure 6.3 shows the differences between ergometer and boat findings of the mean change in lumbar spine angle between the first and last steps of the test.

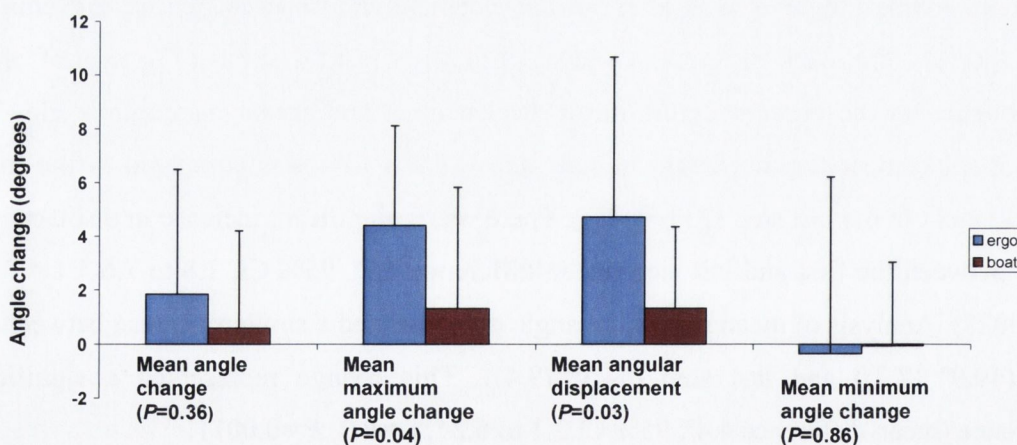


Figure 6.3: Chart to show the differences in mean lumbar spine sagittal angle between ergometer and boat rowing (with SD).

Figures 6.4 to 6.7 show the mean results for all participants ($N=19$) for all stages of the step test. A comparison of findings on the ergometer is made with those in the boat test.

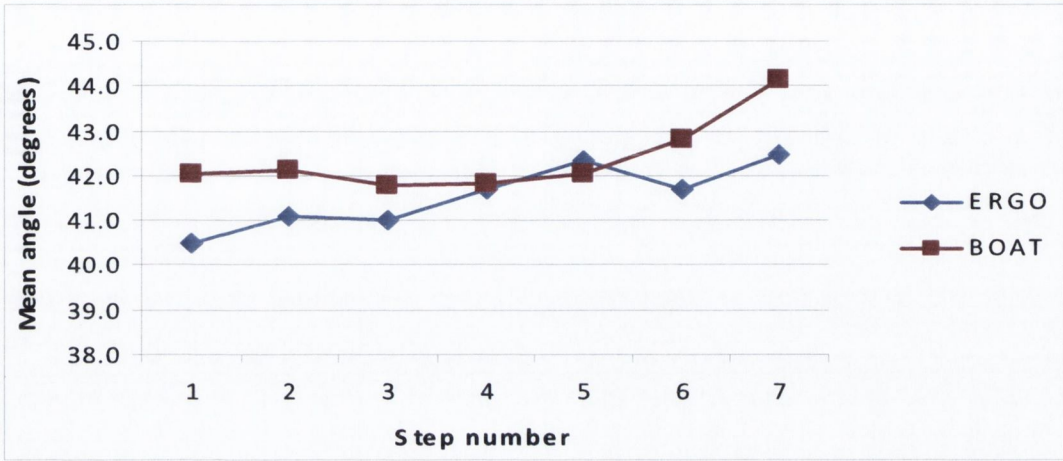


Figure 6.4: Chart to show *mean* lumbar spine sagittal angle over the course of the step test for all participants (mean values, $N= 19$). Ergometer rowing is compared with boat rowing.

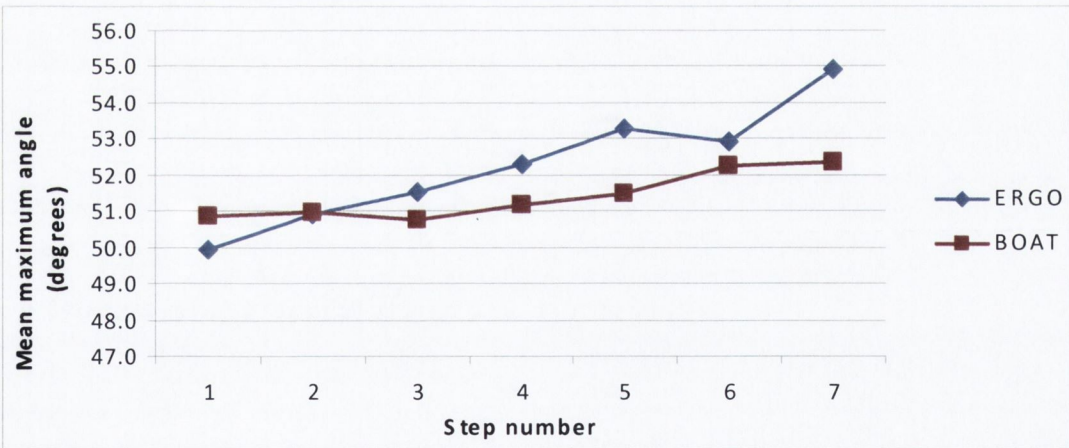


Figure 6.5: Chart to show *maximum* lumbar spine sagittal angle over the course of the step test for all participants (mean values, $N= 19$). Ergometer rowing is compared with boat rowing.

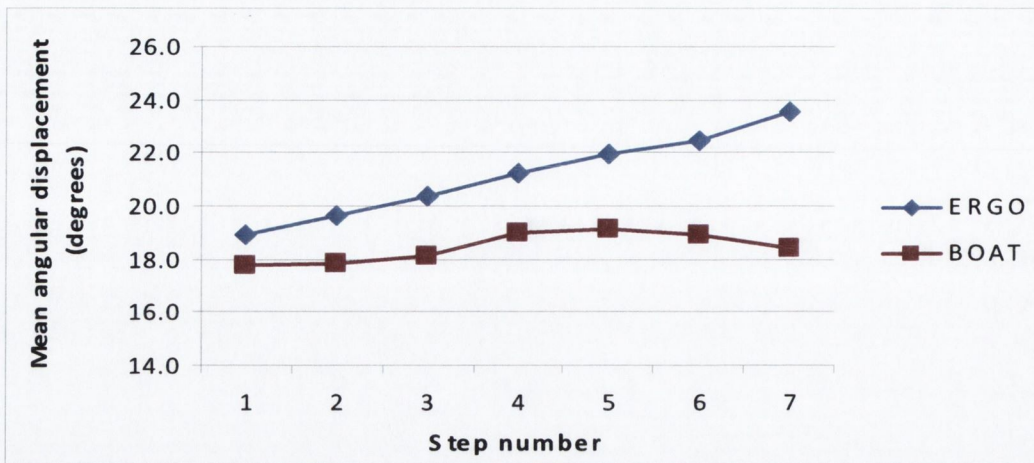


Figure 6.6: Chart to show *angular displacement* of the lumbar spine on the sagittal plane over the course of the step test for all participants (mean values, N= 19). Ergometer rowing is compared with boat rowing.

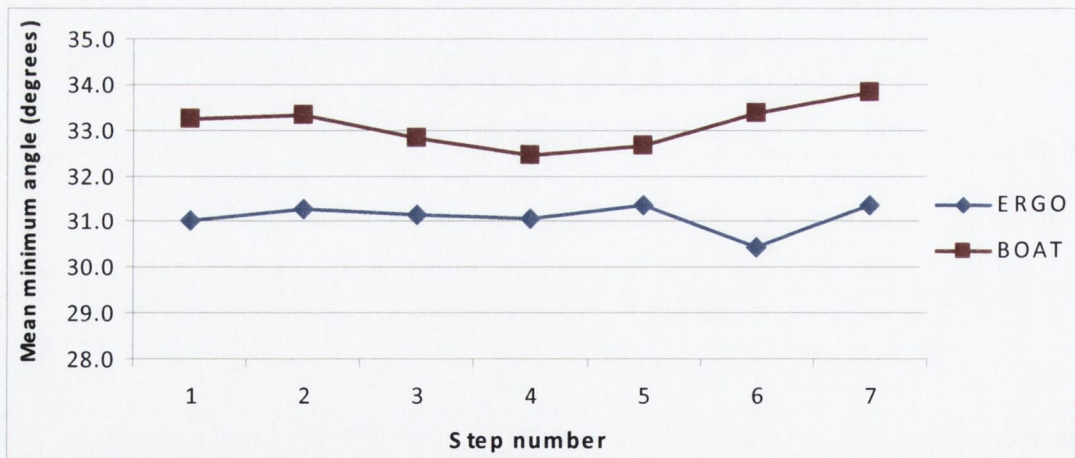


Figure 6.7: Chart to show *minimum* lumbar spine sagittal angle over the course of the step test for all participants (mean values, N= 19). Ergometer rowing is compared with boat rowing.

6.6 DISCUSSION

This study showed that the peak spinal flexion of the lumbar spine was higher in both types of rowing (ergometer and boat) at the end of the test compared to peak spinal flexion pre-test when it was measured in standing. However, it was significantly greater after the ergometer test. In both cases, most individuals reached peak lumbar flexion values that were higher than those seen in full standing flexion (68% of participants following the ergometer test and 63% of participants following the boat test). The fact that the rowers reached high levels of lumbar flexion is in agreement with previous studies (Caldwell et al., 2003, Holt et al., 2003) although values only as high as 89% of peak standing flexion were reported by Caldwell et al. In this study, mean values were in excess of 100% (with a maximum of 139%) of pre-test standing flexion values which indicates that rowers achieve higher values of lumbar spine flexion than was previously thought.

When the sagittal plane kinematics of the lumbar spine was measured during the ergometer test, there were a number of statistically significant findings. Both the mean maximum angle (lumbar spine flexion) and the mean displacement (representing the range through which the lumbar spine moves) increased during the test ($P=0.001$ and $P=0.0028$ respectively). The increase in mean displacement is explained by the fact that there was an increase in lumbar flexion and the spine was returning to the same point at the start of each stroke cycle. Thus, as the rower fatigued, their lumbar spine became more flexed in the sagittal plane. This finding is in agreement with previous studies which examined sagittal kinematics of the lumbar spine during a fatiguing rowing protocol (Bull and McGregor, 2000, McGregor et al., 2005, Caldwell et al., 2003, McGregor et al., 2007, Holt et al., 2003, Mackenzie et al., 2008). A similar pattern however, was not seen when the lumbar kinematics were examined in the boat. Although a small increase was seen in mean flexion angle and displacement, neither of these findings was significant. A search of the literature revealed no previous studies which had measured lumbar spine kinematics in both an ergometer and a boat; thus this is a new finding.

When the sagittal plane kinematic results in the boat and the ergometer were compared directly, a number of significant findings were made. Both mean, maximum lumbar spine flexion ($P=0.04$) and mean angular displacement ($P=0.03$) increased significantly more on the ergometer compared to the boat over the test period (see Figure 6.3). This indicates that as the rowers continue a sustained piece of rowing, their lumbar spines flex more on the

ergometer than the boat. This is the first study to identify the difference in sagittal plane kinematics between the ergometer and boat. Kleshnev (2003) showed that the foot stretcher force (force applied by the feet) develops much earlier on the ergometer as a result of higher inertia forces which the rower has to overcome to change direction of body mass movement, and the handle force on the ergometer has a higher peak and develops later. Kleshnev, (2005) showed that rowers have a 3-5% longer stroke on an ergometer because of an 8-10% longer leg drive. This may explain why the lumbar spine flexes more. Lamb, (1989) showed that the leverage of pull on the oar is greater for ergometer rowing than for water rowing. These factors help explain why a greater increase in lumbar flexion is seen in ergometer rowing as a result of greater 'spinal creep' (see section 7.3.2). However, further work examining the biomechanical differences between water and ergometer rowing is required.

As the mean number of steps completed by the rowers in this study was 6.7, each rower performed approximately 159 lumbar flexion/extension cycles throughout the test period. This study showed that as the rowing trial increased, peak sagittal flexion increased by a significant value on the ergometer, but not in the boat which demonstrated a small mean increase. As each cycle was combined with lumbar loading as the rower pulled on the oar or ergometer handle around the period of peak flexion, a pattern of repetitive cyclic loading is observed. Repetitive cyclic flexion combined with loading of the lumbar spine, has been recognised in a number of studies to increase risk of lumbar spine injury (Solomonow et al., 1999, Parkinson et al., 2004, Gedalia et al., 1999, King et al., 2009b, Marras et al., 1993).

This study has a number of important findings. The results have shown that rowers achieve very high levels of lumbar flexion both in boat and ergometer rowing. It was also found that lumbar flexion steadily increases with continued rowing, peaking as the rower becomes exhausted. Finally, the study showed that there is a significantly greater increase in sagittal lumbar flexion when rowing on an ergometer, compared to rowing in a boat. These results may help to explain why rowers sustain lumbar spine disorders and, in particular, why rowing ergometer training increases risk of this injury as noted in study 1. The implications of the findings of this study and how they may influence onset of injury in rower's lumbar spines will be discussed further in section 7.3.2.

Limitations

As in studies 2, 3 and 4 the participants in this study continued rowing until the point of volitional exhaustion and this may not necessarily be their true measure of fatigue. Thus, an assumption has been made that the point at which the rowers stopped rowing has been because of fatigue. While every effort was made to control for conditions in the rowing trial, it was not possible to measure or control water depth or flow rate which may have affected results. The equipment required for this study needed to be small and portable and because of this will have had inherent degrees of error which was discussed. However, consideration of this still means that the results are meaningful as a general trend was consistently observed in the findings.

6.7 CONCLUSION.

Ergometer rowing is associated with a significantly greater degree of lumbar spine sagittal flexion compared to boat rowing over the period of a rowing protocol. Both ergometer and boat rowing are associated with very high ranges of lumbar sagittal flexion which exceeded full voluntary standing flexion by a mean of 11.3% (ergometer) and 4.1% (boat). Both ergometer and boat rowing were associated with an incrementally increasing range of lumbar sagittal flexion as the rower reached the point of exhaustion due to fatigue over the test period. However, only ergometer rowing showed significant increases in lumbar flexion with boat rowing showing smaller, non significant changes. These factors merit further investigation to confirm how ergometer biomechanics differs from boat rowing and how they are related to lumbar spine injury onset in rowers.

6.8 SUMMARY OF OBJECTIVES FOLLOWING STAGE THREE.

√ = Completed

X = Not yet completed

- To establish an injury profile and identify predictors for injury in rowers √.
- Determine the frontal plane kinematics of the lumbar spine when rowing √.
- Compare the frontal plane kinematics of the lumbar spine when rowing in a boat with rowing on an ergometer √.

- Compare the sagittal plane kinematics of the lumbar spine when rowing in a boat with rowing on an ergometer ✓.
- Examine kinematics of lumbar spine in both the frontal ✓ and sagittal ✓ plane under the conditions of fatigue.
- Compare the kinematics of the lumbar spine when rowing in a boat with rowing on an ergometer, under the conditions of fatigue (frontal plane ✓, sagittal plane ✓).

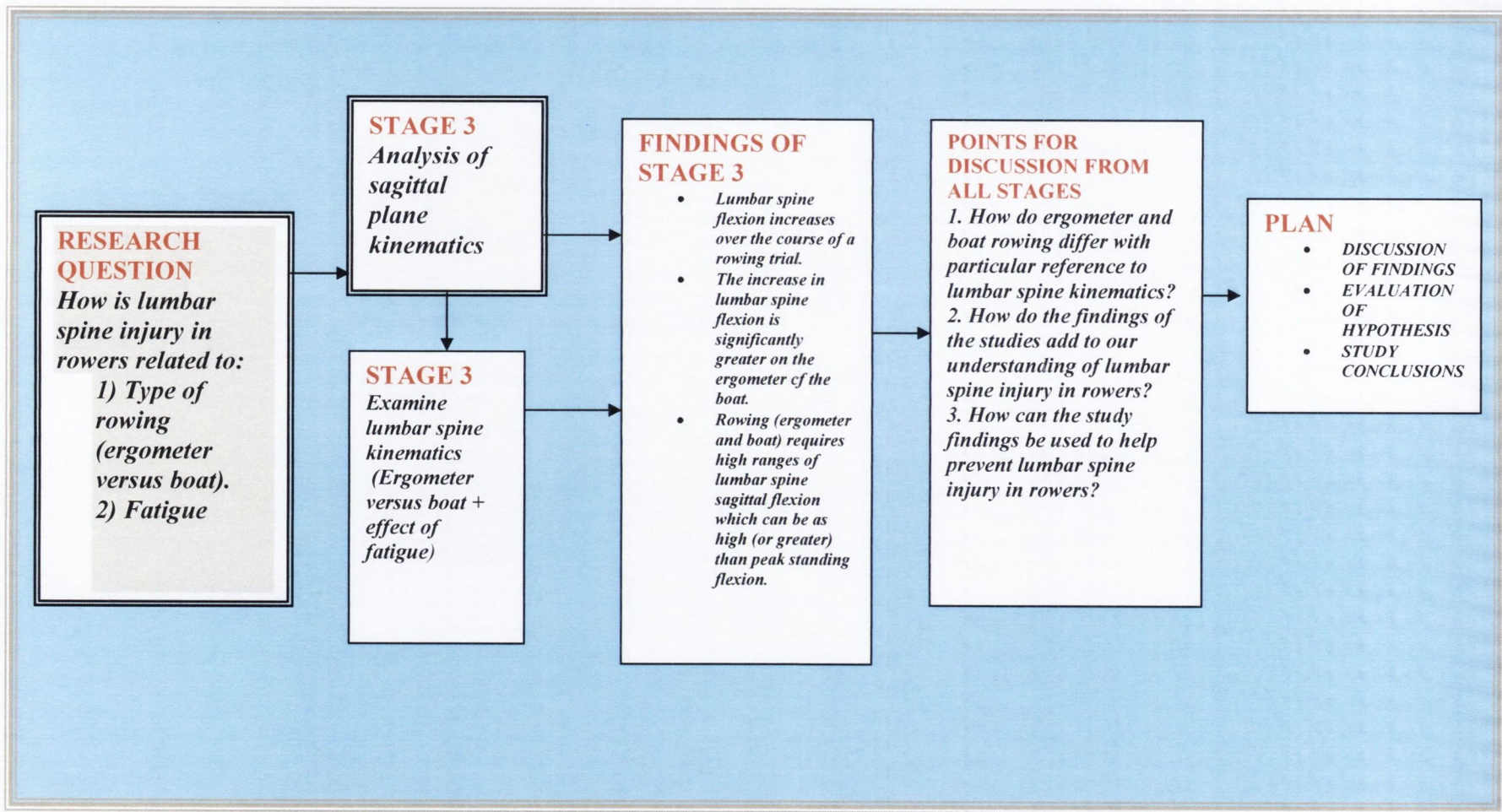


Figure 6.8: Flow chart summarising findings of study 5 and outlining points for discussion.

CHAPTER 7

DISCUSSION

7.1 Introduction and main findings.

The goal of this thesis was to generate a greater understanding of the prevalence and causes of lumbar spine injury in rowers. While previous work discussed in section 1.3.2 had indicated that the most common injury in rowers was to the lumbar spine (Budgett and Fuller, 1989, Smoljanovic et al., 2009, Devereaux and Lachman, 1983, Coburn and Wajswelner, 1993, Hickey et al., 1997, Edgar, 1993), there were a number of methodological limitations which meant that further investigation was required to confirm this finding. The same studies, and those subsequently discussed in section 1.6 indicated that there were a number of factors which may contribute to onset of lumbar spine injuries in this population; these were rowing mode (ergometer or boat) and fatigue. The only study to identify predictors for injury (Teitz et al., 2002) indicated that ergometer sessions of 30 minutes or more increased risk, although many of the other studies suggested that land training rather than boat rowing presented a greater lumbar spine injury risk. The studies reviewed in section 1.6 consistently showed that kinematics of the lumbar spine altered as a rowing session continued which was therefore attributed to fatigue. However, all these studies examined one plane of motion only (the sagittal plane) and none examined kinematics in a boat. A framework for examining injury in sport was outlined by Van Mechelen (1997a) (section 1.3.1, figure 1.9) which stated that the first stage should be to establish the extent of the problem (including incidence and severity) and then to establish aetiology and mechanisms. For this reason, the first stage of the study was to conduct injury surveillance and the following stages examined lumbar spine kinematics on both the boat and ergometer, and under conditions of fatigue, to attempt to understand aetiology and mechanisms of lumbar spine injury in rowers.

Study 1 established an injury incidence of 3.67/1000 hours in the cohort of international rowers assessed over 12 months; this was higher than previously reported in a prospective study at 1.5/1000 hours (Parkkari et al., 2004) or in the most recent (retrospective) study of international rowers at 2.1/1000 hours (Smoljanovic et al., 2009). It was noted that when the injury incidence was put in the context of other sports such as boxing (Zazryn et al., 2006) which has a similar competition to training time ratio, the incidence in rowing was

high (boxing reported as 2/1000 hours). The most common reported injury in rowers was to the lumbar spine (31.8% of all reported injuries) which was sustained by 65% of the cohort over a twelve month period. The factor that was most significantly associated with injury risk was volume of ergometer training which was in agreement with a previous study (Teitz et al., 2002). Those rowers who sustained a lumbar spine injury, did significantly more ergometer sessions during the 12 month period of the study than those who did not ($P=0.049$).

As a result of the findings of study 1, study 2 examined lumbar spine kinematics in rowing, comparing those in a boat with an ergometer. Kinematics were assessed in the frontal plane as it was hypothesised that this was the plane where the greatest difference between the ergometer and the boat could be observed and it was an area which had not previously been examined. The study found that angular displacement of the lumbar spine in the frontal plane was greater on the ergometer (mean of 5°) compared to the boat (mean of 3.4°) and that angular displacement could reach as high as 7.6° . Thus a considerable range of motion was found in the frontal plane which was not in agreement with a previous study which suggested that no movement took place in this plane (Bull and McGregor, 2000). Study 3 examined the effects of a fatiguing protocol on the frontal plane angular displacement in the lumbar spine as study two had noted a small increase over the course of the rowing trial. On this occasion, rowers completed a physiological step test on the ergometer only, as the greatest angular displacement had been noted on the ergometer in the previous study. The mean angular displacement in the frontal plane at L3 ranged from 4.8° to 7.8° for the four subjects. While all subjects showed an increase in displacement over the course of the test, those who showed a statistically significant increase had completed more steps and may have been more fatigued. To introduce an assessment of fatigue, the protocol was repeated in study four when blood lactate accumulation was measured. Study 4 found a mean increase in frontal plane angular displacement over the course of a step test of 4.1° (1.9) which was statistically significant ($P=0.000014$). While blood lactate concentration also increased incrementally in parallel with angular displacement, it was found that only stroke rate was a significant predictor of increasing frontal plane angle. This suggested that further parameters need to be measured to confirm that the changes were due to fatigue.

Studies 2, 3 and 4 concurred with previous studies discussed in section 1.6 which found that spinal angular displacement increased over the course of a rowing trial. However,

these studies provided information regarding the frontal plane which had not been examined previously. The studies confirmed that the same pattern previously observed in the sagittal plane, also occurs in the frontal plane. They also were in agreement with previous studies (again discussed in section 1.6) that showed that angular displacement in the lumbar spine reached maximum voluntary range established previously (Caldwell et al., 2003). The studies in this thesis were able to provide a more comprehensive analysis of the kinematics of the lumbar spine in rowers by examination of a new plane of motion. The studies were able to provide new information regarding the frontal plane and to highlight differences in frontal plane kinematics between ergometer and boat rowing.

The final study of this thesis (study 5) aimed to explore sagittal plane kinematics in the lumbar spine in an aspect which had previously not been examined, by comparing lumbar spine motion in the boat with the ergometer. There was an increase in maximum lumbar spine sagittal flexion over the course of a step test protocol, increasing by a mean of 4.4° (0.9) on the ergometer and increasing by a mean of 1.3° (1.1) in a boat. The increase was significantly greater on the ergometer compared to the boat ($P=0.035$). It was also observed that when the mean maximum lumbar spine flexion was compared to the peak standing voluntary flexion (measured pre-test), it was a mean of 11.2% (15.2) greater at the end of the ergometer test and a mean of 4.1% (10.2) greater at the end of the boat test. This was in agreement with previous studies of ergometer kinematics discussed in section 1.6 but also showed that the increase in sagittal plane lumbar flexion was significantly less over the course of a boat trial than an ergometer trial.

In summary, rowers are at risk of lumbar spine injury and this risk may be increased with exposure to ergometer training compared to boat training. Both ergometer and boat rowing are associated with high values of angular displacement in the mid lumbar spine, in both the frontal and sagittal plane. The values of angular displacement noted in this study were comparable to, or higher than those noted as the (normative) full maximum voluntary range in previous studies (Bogduk, 2005, Li et al., 2009). Both sagittal plane and frontal plane angular displacement increase over the course of a rowing trial which may be as a result of fatigue.

7.2 Differences between ergometer and boat rowing.

Prior to this thesis, no study had examined the differences in lumbar spine kinematics between an ergometer and a boat. The findings of study 1 confirmed that this was

important to improve understanding of this injury in rowers as ergometer rowing was highlighted as an injury predictor. The difficult task of balancing a rowing boat was outlined in section 1.2 and this is probably the most obvious difference between ergometer and on-water rowing. For this reason, it was expected that the motion in the frontal plane would be much greater in the boat than on the ergometer as the boat is unstable in this plane. The results of study 2 showed that the frontal plane motion in the lumbar spine was in fact greater on the ergometer. This finding was initially surprising but could be explained by the fact that the ergometer is 'more forgiving' for poor rowing technique. Excessive lumbar spine frontal plane motion in the boat would cause it to be unbalanced and difficult to row; the same poor technique on an ergometer would have limited influence and the rower could continue rowing regardless. Thus, the boat provides feedback to reduce frontal plane motion in the lumbar spine and the ergometer allows this movement to continue unchecked.

What was perhaps most surprising in studies 2, 3 and 4 was the magnitude of movement in the frontal plane in the lumbar spine. Frontal plane motion in spinal segments is most associated with side flexion of the trunk. Rowing on an ergometer and in a sculling boat should involve minimal (or no) motion in this pattern. The movement ranges in the studies of this thesis were close to those cited as maximum voluntary normal range in previous studies (Li et al., 2009, Bogduk, 2005). This may be because rowers do not move in a smooth fashion through the sagittal plane during the rowing stroke and are constantly adjusting their trunk. This may be explained by asymmetries in rowers' trunk muscles which was discussed in section 1.6.3 (Parkin et al., 2001). Although all rowers in this study were primarily scullers, many also competed at elite level as sweep rowers which may mean that they had asymmetries in their trunk musculature. Further, it is likely that the rowers in this study also had a dominant arm and leg which would pull the trunk into side flexion during the rowing stroke. Pulling harder with one arm or pushing harder with one leg on an ergometer would have little effect on technique. In a boat, it would cause it to be unbalanced and the blades to alter their movement pattern through the water making it difficult to row. Further studies to examine the range of frontal plane motion in the lumbar spine of sweep rowers both on an ergometer and in sweep boats may explain this finding further.

Study 5 concurred with previous studies discussed in section 1.6.1 (summarised in Table 1.2) that found that sagittal plane motion in the lumbar spine reached high values, but it

also provided new information and demonstrated that the range of motion was higher on the ergometer compared to the boat. This may be explained by the findings of Lamb (1989) who found that the leverage of pull on the oar is greater for ergometer rowing than for water rowing and by Kleshnev (2003) who showed that the foot stretcher force develops much earlier on the ergometer as a result of higher inertia forces which the rower has to overcome to change direction of body mass movement. Such aspects may cause greater loading on the lumbar spine at the catch on the ergometer, inducing greater lumbar flexion. Kleshnev (2005) also showed that rowers have a 3-5% longer stroke on an ergometer and the findings of study 5 suggest that the longer stroke length is achieved by increased lumbar spine sagittal flexion. All rowers in studies 2 and 5 carried out the rowing trial in their own single sculling boats which conformed to FISA racing standards. Although these boats were standardised for the trial in terms of oar gearing and rigging set up (see section 1.1.2) the participants adjust the foot stretcher length for their individual height (see Figure 1.0). Section 1.2.2 discussed the anthropometrics of rowers, noting that they are tall individuals with long limbs. The Concept 2 ergometer is a standard size and can only be adjusted at the foot plate for comfort (see Figure 1.3). The increase in lumbar sagittal flexion noted on the ergometer could be a reflection of taller individuals adopting the required posture to accommodate to the Concept 2. Further research is needed in this area.

7.3 How do the findings of the study add to our understanding of lumbar spine injury in rowers?

7.3.1 Lumbar spine injury in rowers in comparison to normative data.

To put the incidence of lumbar spine injury in rowers into context, it needs to be compared to the incidence of the same injury in the normal population. The incidence of lumbar spine injury in this study was 65% of the population sample over the 12 month study period. Comparison presents with some difficulty due to varying definition of injury (see section 1.4.1) although some evaluation can be made. Palmer et al. (2000) reported a 12 month (retrospective) prevalence of 49.1% although when data was analysed to only include those subjects who reported 'low back pain making it impossible to put on hosiery' only 2.7% of the cohort reported pain of this severity. Croft et al., (1999) reported new episodes of back pain over a 12 month period in a mean of 25.3% of male subjects and 25.3% of females. Even when compared to the study which reported the highest incidence, it appears that the risk of lumbar spine injury in rowers is much higher than in the normal population.

7.3.2 The effect of kinematics on mechanism and type of injury.

Kinematics and loading as risk factors

The lumbar spine kinematics that were measured in the studies of this thesis were done in two movement planes; the sagittal plane and the frontal plane. The functional anatomy of the lumbar spine was examined in section 1.5.1 and described how the majority of movement in the lumbar spine takes place in these planes due to the orientation of the apophyseal joints. There has been a small amount of movement measured in the transverse plane (between 1.7° and 1.2°, depending on the segment level) in a recent study (Fujii et al., 2007), although it was found that the level of accuracy of the equipment used in the studies of this thesis meant that meaningful data could not be collected in this plane. It should be noted that section 1.5.1 also emphasised that all movements in the lumbar spine are coupled. The movements measured in the studies of this thesis would have also been accompanied by movement in the two other planes. As the studies were done on sculling boats, it was expected that spinal rotation (transverse plane motion) that is observed in sweep rowing would be absent although research is required to examine if this is present in scullers.

Studies 2 to 5 all showed that angular displacement in the lumbar spine was at or near maximum values (in both the frontal and sagittal plane) that were found in normal subjects in previous studies (see section 1.5.2). To understand how this links with risk of injury to the lumbar spine, a number of factors should be deliberated. Although the range of motion is at end range, tissue loading will depend on the forces acting at the same time. The point of maximum flexion of the rower's lumbar spine closely corresponds with the point at which the spine is loaded when the oar is placed in the water and the rower starts to apply force. This is comparable to lifting a weight with a flexed lumbar spine. Dolan and Adams, (2001) note that lifting weights from the ground requires the lumbar spine to be flexed by 70-80% of full standing flexion (toe touching) stating that 'when the spine is flexed by this amount, substantial tension is generated in non-contractile tissues of the back'. Wilke et al., (1999) noted mean intradiscal pressure at (L4/5) of 2.30MPa when lifting a 20kg weight with a 'bent over round back' and a pressure of 0.83MPa when sitting with maximum lumbar flexion, and Sato et al., (1999) noted horizontal intradiscal pressure in sitting at L4/5 as 1133kPa. Only one study has examined the forces acting on the lumbar spine in rowers (Morris et al., 2000). Peak compressive and shear forces at L4/5 were calculated as $2730 \pm 609\text{N}$ and $693 \pm 117\text{N}$ respectively. Peak compressive forces

generated at the lumbar spine expressed relative to the subjects' body weight was 4.6 times the rowers' body weight. Thus, in rowing, end range lumbar motion (both in the frontal and sagittal planes) is combined with considerable loading. To understand the risk this poses to injury onset, research examining similar movement and loading patterns and injury risk needs to be considered.

The results of study 5 suggest that the rower's lumbar spine behaves in a manner consistent with other studies which examined the influence of loading in flexion. This could have important implications for understanding why rowers injure their lumbar spine. Cadaveric experiments suggest that in bending and lifting activities, injury to the lumbar discs and ligaments 'is most attributable to a high bending moment acting on the spine' (Dolan and Adams, 1994). While 'bending can sprain the ligaments of the neural arch, bending and compression can cause the intervertebral disc to prolapse (Dolan and Adams, 1993). The fact that rowers achieve such high levels of sagittal plane flexion which is then combined with loading, correlates with work place studies which have cited both of these factors as risk for low back injury (Marras et al., 1993). Individually, these factors increase injury risk, but when combined as in this case, risk is increased further. A number of studies have found that the combination of flexion and 'twisting', combined with loading was a specific risk factor for onset of low back pain (Marras et al., 1993, Mundt et al., 1993, Hoogendoorn et al., 2000). Such motion patterns are seen in studies 2 to 5 of this thesis. While 'twisting' is poorly quantified in all of the studies, it is likely to be a combination of frontal and transverse plane motion. Thus, risk factors which are well established in the study of low back pain have been found to exist in rowers following examination of the results of study 2 to 5.

Effect of fatigue and tissue creep

Repeated cyclical loading has been noted as a risk factor for lumbar spine injury in a number of previous studies (Marras et al., 1993, Hoogendoorn et al., 2000, Mundt et al., 1993, Marras et al., 2006, Norman et al., 1998). In studies 2 to 5, range of motion in the lumbar spine increased over the course of the rowing and ergometer trials both in the frontal and sagittal planes. Cyclical loading induces 'creep' in the tissues allowing an increase in initial range of motion and may increase risk of injury in a number of ways (Solomonow et al., 1999). Solomonow et al., (1999) found that the creep induced in the viscoelastic tissues of the spine desensitises the mechanoreceptors within which 'is manifest in dramatically diminished muscular activity allowing full exposure to instability

and injury even before fatigue of the musculature sets in'. This indicates that the reflexive muscular stabilising forces in the lumbar muscles are compromised increasing risk of injury. Dolan and Adams (1998) and Gorelick et al., (2003) found that the fatigue in the lumbar extensor muscles (which would be expected, as the rowers completed the test to exhaustion) allowed the increase in lumbar flexion with an associated increased bending moment which increases injury risk. However, more recent work (Sanchez-Zuriaga et al., 2010) has suggested that it may be the tissue creep rather than muscle fatigue that impairs sensorimotor control mechanisms. The fact that repeated loaded cyclical flexion compromises neuromuscular control (leading to increased injury risk) has been confirmed in a number of other studies (Dickey et al., 2003, Solomonow et al., 2003, Sanchez-Zuriaga et al., 2010). The creep behaviour described has generally been associated with risk of injury but further evidence confirms specific damage to lumbar tissues, most notably intervertebral disc (Heuer et al., 2007, Callaghan and McGill, 2001) but also vertebral bodies and endplates (Van Der Veen et al., 2008) and facet joint capsule (Little and Khalsa, 2005). Further evidence to explain why creep loading may lead to injury is explained by the findings of Solomonow et al., (2003) and later, King et al., (2009b) who found that prolonged cyclical loading of the lumbar spine in flexion/extension not only elicits creep but also causes significant increases in cytokines expression, which is consistent with acute inflammation for several hours after the activity. King et al., (2009b) suggest that if the inflamed lumbar spine is continued to be exposed to repetitive loading on a daily basis this may lead to 'conversion to chronic inflammation, degeneration of the viscoelastic tissues into fibrous non-functional tissue and the associated mechanical and neuromuscular disorders and loss of function'. Elite rowers frequently row in a boat or ergometer on a daily basis which means that the loading described above is indeed regular and sustained; this may help to explain the high incidence of lumbar spine injury in this group.

Adams et al., (1999) suggested that tissue creep is caused by muscle fatigue but they also suggest that it is also caused by a combination of 'physical metabolic and psychological factors'. Blood lactate accumulation was measured in study 4 as a measure of fatigue but analysis of results showed that it was a poor predictor of kinematic changes. Although the nature of the incremental step tests carried out in studies 3 to 5 suggests that the participants must have been fatigued at the test end, more measures are needed to confirm this.

There has been limited analysis of lumbar spine muscle activity in rowing (see section 1.6.3) although Caldwell et al., (2003) showed that muscle activity increased significantly as a rowing trial progressed from levels of 50% maximum voluntary contraction (MVC) to 80% MVC. Caldwell compared this to levels of 35% and 40% MVC of multifidus when lifting a heavy box weighing 250N and concluded that muscle activity by the end of the rowing test was very high. This suggests that the spinal creep observed in studies 2 to 5 may have been as a result of muscle fatigue but further research into muscle activity in rowing is required to verify this.

It is likely that both fatigue and tissue creep observed in studies 2 to 5 increase the risk of injury to the lumbar spine of rowers and this area warrants further research.

Type of injury

Study one reported lumbar spine injury in 65% of the cohort. Four of the injuries were reported as 'disc injury', 7 as 'facet joint injury', 2 as 'muscle strain' and 1 as a 'contusion'. All these injuries were self reported, but the diagnosis had been provided to the participants by a number of chartered physiotherapists or medical doctors who were associated with the Irish Rowing Team. It was not quantified how many of these injuries were confirmed by investigation and it is likely that most were diagnosed by clinical assessment only, so it is unknown if diagnoses were correct. As discussed in section 1.4.3, the causes of low back pain are frequently multi-factorial. However, analyses of the current results indicate that it is possible to surmise what tissues of the lumbar spine may be affected.

The results of studies 2 to 5 showed that patterns of end range sagittal and frontal plane flexion are combined with loading. High ranges of these movement patterns were noted, indicating that rowers are at or beyond their maximum voluntary range. A creep response was observed, combined with possible fatigue of lumbar musculature. The role of the intervertebral disc in the lumbar spine was discussed in section 1.5.1. It was noted that the annulus and nucleus work together to sustain compressive loads (Dolan and Adams, 2001) and that an increased compressive load on the neural arch is caused by long term 'creep' loading and that a high anterior disc compressive force is noted in high ranges of flexion (Hedman and Ferney, 1997). The repeated cyclical loading (repeated flexion/extension pattern) and high levels of spinal flexion exhibited by the rowers in the studies of this

thesis have been shown to cause lumbar disc bulging (Heuer et al., 2007) herniation (Callaghan and McGill, 2001) and facet joint capsule strain (Little and Khalsa, 2005). Compression forces noted in the rowers lumbar spine by Morris et al., (2000) are comparable to those seen during lifting which can cause fractures of the vertebral endplates (Van Dieen et al., 2002).

Section 1.5.1 discussed the role of the various ligaments of the lumbar spine in controlling movement; their primary role is resisting separation at end range motion. It is therefore likely that high tensile forces and resulting tissue damage are observed in the ligaments that resist frontal and sagittal plane motion in the lumbar spine. Hedman and Ferney (1997) found that the facet capsules, posterior longitudinal ligaments and posterior annulus contributed more than three quarters of the resistance to lumbar flexion. Further, the micro damage and associated inflammation in the spinal ligaments (discussed above) highlights how acute ligamentous damage may become chronic. Studies examining the effects on muscle of the motion patterns observed in the lumbar spines of rowers in this thesis, have focussed on impairment of sensorimotor control mechanisms and changes in their functional capacity (Sanchez-Zuriaga et al., 2010). The reflexive activation of multifidi and longissimus muscles is significantly decreased during repetitive motion (Little and Khalsa, 2005). It is therefore likely that rowers suffer such impairments in sensorimotor control and associated reduction in muscular protection of the underlying spine.

Thus the results of the studies suggest that rowers are at risk of sustaining damage to a variety of structures of the lumbar spine, notably the disc, ligaments and facet joint capsule as well as impairment in muscle function. A longitudinal injury surveillance programme which includes investigations would provide more information in this area.

7.3.3 How can the study findings be used to prevent lumbar spine injury in rowers?

As only one clear predictor for lumbar spine injury was identified in study 1 (volume of ergometer training), this is the area that should be addressed first. Rowers routinely spend a lot of time training on the ergometer, especially in countries like Ireland where winter weather conditions can limit boat rowing. The results of this thesis suggest that ergometer rowing should be limited. Of particular concern is that rowers may precede a weight training session with a warm up on the ergometer and the spinal creep that was noted on the ergometer may increase the chance of a lumbar spine injury if the rower then lifts

heavy weights. The length of the ergometer session should be reduced as risk of lumbar spine injury increases with the number of loading cycles (Hoogendoorn et al., 2000, Marras et al., 2006). Lumbar spine range of motion in both the frontal and sagittal plane increased as the rowers continued rowing in studies 2 to 5, which may have been because of fatigue. This suggests that both boat and ergometer sessions should have a time limit. Some very limited research to date has suggested that the Rowperfect ergometer may present less injury risk to rowers as the stroke length is shorter (Bernstein et al., 2002) which indicates that it may be beneficial to replace the Concept 2 with such a machine. This is discussed further in section 7.5. Section 1.2.2 discussed the anthropometrics of rowers, highlighting that they are tall individuals with long limbs. The Concept 2 ergometer is a standard size and the only adjustable component is the footplate height (see Figure 1.3). Sculling boats have many adjustable components and as such may be a 'better fit' for taller rowers. Adaptations to the Concept 2 that may benefit taller rowers would be to include an adjustable 'stretcher' (see Figure 1.0) as in a sculling boat which would accommodate longer legs more comfortably. This may allow a more optimal position of the hips and lumbar spine.

The studies performed suggest that protocols which optimise lumbar spine posture should be adopted by rowers. An ability to limit the increase in sagittal or frontal plane motion in the lumbar spine may protect the rower from injury. Traditionally, core stability training aimed to do just that, by stabilising the lumbar spine into a neutral position. However, study 1 showed that core stability training seemed to offer no protective effect for lumbar spine injury. While this could be due to a poor understanding of what constitutes such training, it could also be because a generic training programme was used which did not address the specific problems highlighted by this thesis. Core stability training places an emphasis on endurance activity in both the trunk flexors and extensors of the lumbar spine. However, Pollock et al., (2009) showed that during the period of peak force production there were minimal amounts of co-activation among the flexors and extensors of the trunk, demonstrating that there was very little trunk flexor activity during the drive phase. While the extensors represented 60% of muscle activity during the period of peak force production, the flexors only represented 6%. The fact that low levels of abdominal muscle activation (flexors) were observed at the period of peak force production seems to negate the commonly held belief that the abdominal muscles are important in spine stabilisation. If the abdominal muscles were working harder during this period, it would negatively impact on the force produced by the extensors and consequently the power of the stroke

(Pollock et al., 2009). Pollock et al suggest that increased co-activation of the flexors and extensors would also result in increased compressive spinal forces and may contribute to injury. Thus it appears that 'core stability' programmes should be replaced by exercise that places emphasis on endurance of the trunk extensors to reduce increases in sagittal plane flexion and maintain stroke power. The findings of the studies examining frontal plane kinematics suggest that exercise to correct lumbar spine muscle asymmetries may also have a protective effect.

7.4 Critical analysis of this work.

The injury surveillance method used in study 1 was designed to reflect best practice as far as possible (see section 1.3.1). However, some limitations were noted. The monthly reporting of data may have introduced a retrospective element although all participants kept training diaries to improve reporting accuracy. The cohort used in this study was specific in that they were all international rowers competing in a training year which culminated in the Olympic Games. Thus the results may not generalise to the wider rowing population. All but two injuries were diagnosed by a chartered physiotherapist or a doctor but it cannot be quantified how accurate such diagnoses were. For the reasons discussed in section 1.3.1, ergometer rowing cannot be described as a 'risk factor' for lumbar spine injury in rowing, but rather an association or predictor for injury. Further work is required to establish specific risk factors.

Studies 2 to 5 were based on lumbar spine kinematic analysis. A possible source of inaccuracy was degree of error of the equipment which was discussed in each section. As both the Spectrotilt inclinometer (maximum error of 0.5° noted, see Appendix C) and Biometrics Electrogoniometer (maximum error of 0.45° noted, see Appendix H) were placed over the skin, one cannot be sure that the equipment was placed at the anatomically correct site or that skin movement over the vertebrae produced error. To limit error as far as possible, the same researcher (Fiona Wilson) always placed equipment in situ and maximum effort was made to ensure that no slippage of equipment occurred. Bull and McGregor, (2000) noted a mean error of 1° when mounting blocks placed on the skin surface were compared to MRI. It is therefore likely that the source of error in the studies of this thesis is at this level due to skin surface movement. The equipment needed to be simple and portable to fulfil the functions required for the studies. More complex laboratory based motion analysis systems such as the 'Flock of Birds' used in previous

studies (Bull and McGregor, 2000, McGregor et al., 2004, McGregor et al., 2005, McGregor et al., 2007) would have allowed a greater degree of accuracy to be assured. However, such a system could not have been used for testing in a boat. The studies of this thesis received no direct funding and the equipment and methods used were the most economically efficient. Both the Spectrotilt and EGM displayed a degree of error of 0.5° which was noted in calibration studies. Taking this into account and that associated with skin surface motion (1° of error) reported by Bull and McGregor, (2000) the results of this thesis are still meaningful and significant in those studies which were reported so.

All the participants in the studies of this thesis were rowers who had reached an elite standard of rowing and who were primarily scullers. This was to ensure that the findings during kinematic analysis were not a reflection of poor technique. Sculling is a complex skill to learn and thus this limited the population sample available for all studies. Thus the studies may not be necessarily applied to rowers who are primarily sweep rowers or to those who are less experienced.

In terms of equipment used, all ergometer testing was carried out on Concept 2 ergometers as this is the machine used most frequently by rowers and correlates best with rowing skill (Mikulic et al., 2009a). However, some rowers use other types of ergometer such as the 'Water Rower' and the 'Rowperfect' which may give different results (see section 1.2.4). In boat rowing, all rowers used their own single scull which was standardised for racing according to the requirements of FISA. However, seat type, age, footplate set up and make of boat varied which may have introduced differences. All rowers used the same type of oars in the boat studies.

Weather and environmental conditions influence boat rowing. All efforts were made to control for such by measuring wind speed and ensuring that all rowing trials were conducted on the same stretch of water in the same direction. However, it was not possible to fully control for water depth and tidal flow. As it is not possible to measure work output in a boat, this was measured using heart rate. This method is supported by the work of Gueval et al., (2006) who found that physiological parameters were similar for boat and Concept 2 rowing.

The greatest limitation in the studies of this thesis was the size of the population sample that was available for research. Ireland is a small rowing nation with a small international

squad which is limited to a maximum of approximately 20 rowers. The second year of this study (during which study 2 was conducted) saw many international rowers retire and others move abroad. There was no international coach appointed by the IARU for the whole of this season, so there was effectively no national squad. This meant that there was a very small pool of scullers competing at elite level. The following year saw the appointment of an international rowing coach who preferred to train the team outside Ireland, so most of the rowers were again unavailable. The studies of this thesis required that the participants were very accomplished scullers and were experienced in completing physiological step tests. All participants in the studies fulfilled this requirement and most competed at international level. More statistically significant data may have been produced, particularly in studies 2 and 3 if more participants had been available. However, the skill level of the participants were standardised which means that the findings of the studies were not related to varying technical ability. Ireland's largest pool of rowers is based in university clubs which do not have a tradition of elite sculling. Despite these limitations, some of the findings of the studies were innovative. Study 1 was the first to conduct a prospective study of injury and therefore identify predictors for injury. Studies 2 to 4 were the first to analyse kinematics of the lumbar spine in the frontal plane and studies 2 and 5 were the first to produce an analysis of lumbar spine kinematics which compared boat rowing with ergometer rowing. It is important to note that the ability to access a large group of skilled rowers for research purposes is also likely to have been a limitation of all the studies reviewed in section 1.6.1 (see table 1.2). All previous studies which performed kinematic analysis of the lumbar spines of rowers had participant groups of 20 or less. The maximum number of participants was in the study by McGregor et al., (2002) ($N = 20$) and the smallest number was in the study by Mackenzie et al., (2008), ($N = 6$). The mean number of study participants in all the studies reviewed in section 1.6.1 was 11. The mean number of participants in the studies of this thesis was 10.

7.5 Future research.

The studies of this thesis have raised a number of questions for further research. The framework for the study of sports injury highlighted in section 1.3.1 (figure 1.9) by Van Mechelen, (1997a), outlines the stages of the process. The first stage of Van Mechelen's framework is to establish the extent of the injury problem and this formed the basis of study 1. The second stage of the framework is to examine the aetiology and mechanism of the injury and this formed the basis of the studies 2 to 5. The third stage of Van Mechelen's framework is to introduce a preventative measure followed by the fourth stage

which is to repeat the original injury surveillance programme. A logical step would therefore be to eliminate (or, more realistically reduce the volume of) ergometer training in rowers schedules, repeat the injury surveillance programme and analyse the effect on lumbar spine injury. Other preventative interventions that could be introduced are specific exercise programmes aimed at reducing spinal creep such as those discussed in section 7.3.3 above.

It is likely that changing rowers' behaviour regarding ergometers will be difficult as they are such an integrated part of modern training and team selection, so an obvious adaptation could be to alter the design of ergometers. The Concept 2 model C and D that was used throughout the studies of this thesis has what is known as a fixed head (see figure 1.3) i.e. the flywheel does not move. Recent attention has been focussed on the use of an ergometer with a 'floating head' which has a flywheel that moves backwards and forwards. This ergometer is called the Rowperfect (Care Rowperfect BV, JV Hardenberg, Netherlands) and it produces a different rowing pattern. Bernstein et al., (2002) compared the Concept 2 ergometer (fixed head) with the Rowperfect (floating head) and found that the stroke length was longer and the mean forces were higher on the fixed head ergometer. A shorter stroke length is likely to cause less lumbar spine flexion and may reduce risk of injury. No research has been done examining the influence of the different types of ergometer on lumbar spine kinematics. Repetition of studies 2 to 5 of this thesis using the Rowperfect or any other rowing ergometer may indicate that there is a machine which presents less risk of injury.

The original injury surveillance programme could be improved with the use of weekly web based training diaries, more specific injury diagnosis and more in depth analysis of specific training aspects such as core stability. Web based programmes are more economically efficient and may allow a larger, more diverse cohort to be examined. To provide a clearer indication of injury severity, different definition of injuries and severity should be considered as discussed in section 2.6.

As all the participants in the studies of kinematics were scullers, there would be merit in analysis of rowers who are sweep rowers only. When the risk factors for low back pain are considered (see section 7.3.2 above) it seems likely that the trunk rotation that is required for sweep rowing (see Figure 1.8) is an increased risk for this group. Also, analysis of how differing ergometer, boat and oar types influence spinal kinematics in rowers would

expand the information gleaned so far. The sample size of the studies was limited by the level of skill required to complete the tests competently. Further research could extend the study population to outside Ireland to capture a larger cohort. This would also allow a larger group of sweep rowers to be analysed.

One of the factors examined in this thesis was the effect of fatigue on lumbar spine kinematics. It became clear that fatigue was difficult to quantify as the step test protocol tests to the point of volitional exhaustion. Further studies would benefit from inclusion of a number of measures of fatigue to include physiological and psychological. This may provide clarity regarding fatigue definition.

Section 1.6.3 reviewed a small number of studies which examined muscle activity in the lumbar spine of rowers. All these studies were done on a rowing ergometer. Further analysis of lumbar spine muscle activity both in a boat and on an ergometer would prove a useful adjunct to kinematic data in improving understanding of lumbar spine injury in rowers.

7.6 Conclusion.

The first objective of this thesis was to *establish an injury profile and identify predictors for injury in rowers*. Study 1 found that the incidence of injury in rowers is 3.7/1000 hours which is high when compared to sports with similar training to competing time ratios such as boxing (injury incidence of 2/1000 hours, Zazryn et al., (2006)). The most common injury was to lumbar spine (31.8% of all injuries) which was reported by 65% of the cohort in the 12 month study period. This compares with the highest previous reported in the normal population of 49.1% in the same time frame (Palmer et al., 2000). The volume of time spent training on the ergometer was the factor significantly associated with risk of injury.

The second and third objectives of this study were to *determine the frontal plane kinematics of the lumbar spine when rowing and compare the frontal plane kinematics of the lumbar spine when rowing in a boat with rowing on an ergometer*. Frontal plane lumbar spine kinematics reached an angular displacement value which exceeded previous values of full available range (Li et al., 2009) by as much as 26 % during ergometer rowing. Frontal plane angular displacement during ergometer rowing ranged from a

maximum of 5° (study 2), to 10.5° (study 3) and 11.7° (study 4). The maximum range of frontal plane angular displacement during boat rowing was 3.4° (study 2). Frontal plane angular displacement in the lumbar spine differed between boat and ergometer rowing; the ergometer was greater by a mean of 1.6° although this was not statistically significant. It was also observed that the frontal plane angular displacement increased over the course of a trial on the ergometer, but not the boat although this value did not reach statistical significance.

The fourth objective of the study was to *compare the sagittal plane kinematics of the lumbar spine when rowing in a boat with rowing on an ergometer*. Ergometer rowing was associated with a statistically significant increase in lumbar spine sagittal flexion compared to boat rowing over the period of a rowing protocol (4.4° (0.85) compared to 1.3° (1.1) increase respectively). Both ergometer and boat rowing were associated with very high ranges of lumbar sagittal flexion which exceeded full voluntary standing flexion by a mean of 11.3% (ergometer) and 4.1% (boat).

The fifth and sixth objectives of this study were to *examine kinematics of lumbar spine in both the frontal and sagittal plane under the conditions of fatigue* and to *compare the kinematics of the lumbar spine when rowing in a boat with rowing on an ergometer, under the conditions of fatigue*. Ergometer rowing was associated with a statistically significant increase in frontal plane angular displacement in the lumbar spine (a mean increase of 4.1°) over the course of an incremental rowing exercise test. While increases in blood lactate concentration were associated with the increase in angular displacement, blood lactate was not found to be a significant predictor of angular displacement but an increase in stroke rate was. When ergometer and boat rowing were compared, the mean angular displacement in the frontal plane of the lumbar spine was greater during ergometer rowing than boat rowing over the course of a rowing trial.

Both ergometer and boat rowing were associated with an incrementally increasing range of lumbar sagittal flexion as the rower reached the point of exhaustion over the test period. However, the increase in lumbar sagittal flexion was significantly greater during ergometer rowing compared with boat rowing ($P=0.035$).

Thus the incidence of lumbar spine injury is high in comparison to that in the normal population. Volume of time spent ergometer training is a predictor for this injury. Analysis

of lumbar spine kinematics demonstrates a number of differences between boat rowing and ergometer rowing. In both the frontal and sagittal plane, the degree of lumbar spine angular displacement is greater during ergometer rowing than boat rowing. The degree of angular displacement increases over the course of a rowing trial in both the sagittal and frontal planes, which may be as a result of fatigue. In the sagittal plane, the increase in angular displacement over the course of a trial is significantly greater during ergometer rowing than during boat rowing. Both ergometer and boat rowing require large ranges of motion in the lumbar spine in both the sagittal and frontal planes and such range of motion is as high as, or exceeds maximum voluntary range established by pre-test examination or previous research. Further work is required to assess how these findings are related to development of injury in the lumbar spines of rowers and to investigate how training protocols should change to reduce the risk of this injury.

7.7 Evaluation of the study hypothesis.

The hypothesis stated in section 1.7.1 was:

The risk of sustaining a lumbar spine injury in rowing is significant and is influenced by rowing mode (ergometer or boat) and fatigue.

Study 1 showed that the risk of sustaining a lumbar spine injury in rowing is significant and that time spent ergometer rowing increases the risk of this injury. Furthermore, studies 2 to 5 indicated that both rowing mode and fatigue may influence the onset of this injury. The high maximum range of sagittal and frontal plane motion noted in the lumbar spine both in ergometer and boat rowing may increase risk of injury. However, the maximum range of motion was higher in both planes during ergometer rowing, indicating that this mode of rowing may introduce a greater risk of lumbar spine injury. Range of lumbar spine motion increased incrementally in both the frontal and sagittal planes during the course of a fatiguing protocol. However, the increase was greater during ergometer rowing compared to boat rowing. This indicates that fatigue may have an influence on risk of lumbar spine injury as onset of exhaustion seems to be related to an increase in range of motion in the lumbar spine.

In conclusion, the evidence from the injury study and the rowing experiments reported in this thesis corroborate the hypothesis that the risk of sustaining a lumbar spine injury in rowing is significant and is influenced by rowing mode (ergometer or boat) and fatigue.

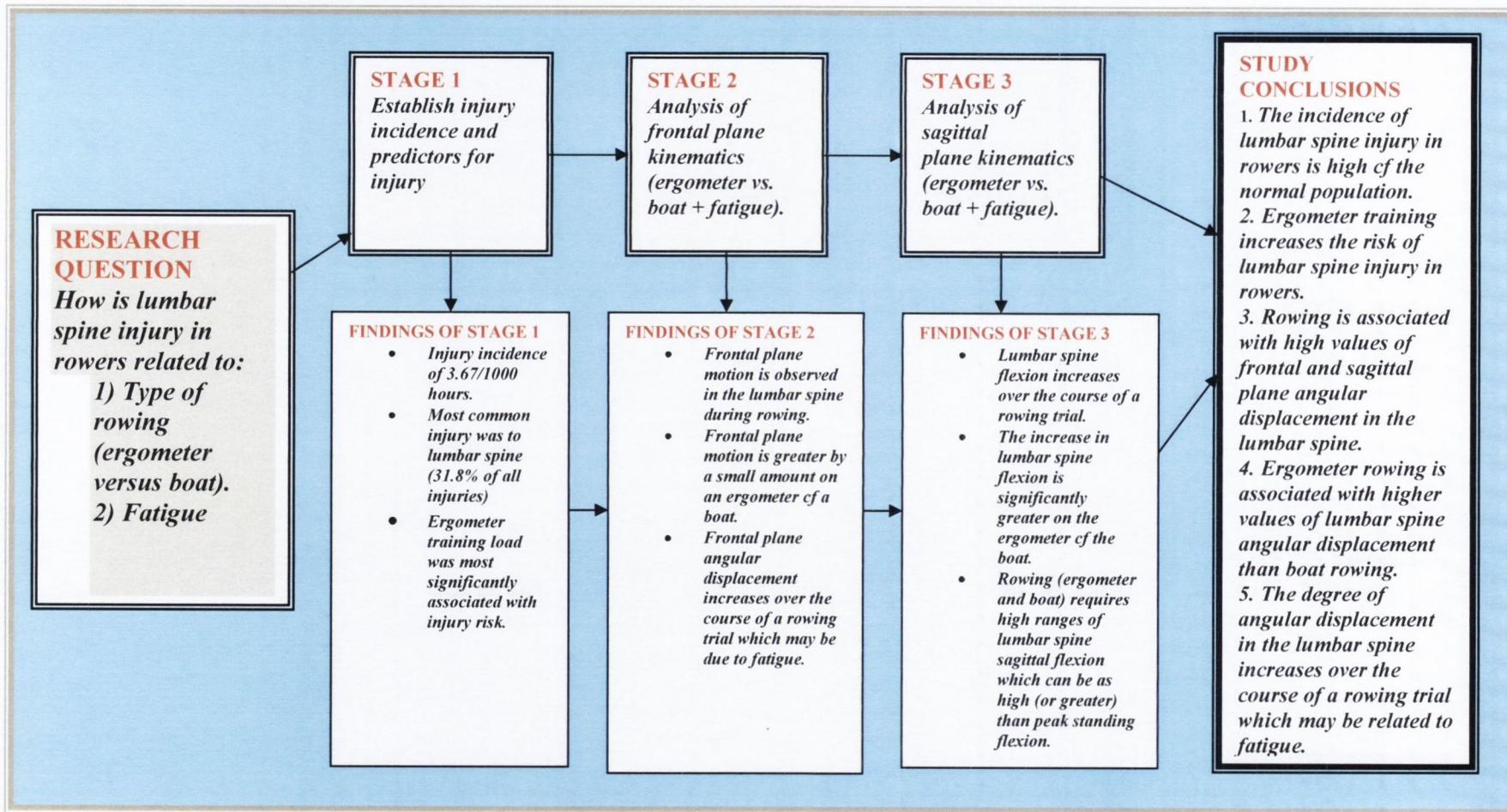


Figure 7.1: Flow chart summarising the stages and conclusions of the studies of the thesis.

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APPENDIX A

BASELINE QUESTIONNAIRE, STUDY 1

SECTION 1: GENERAL DETAILS

Today's date ___ day ___ month ___ year

Gender: Male Female

Age: ___ years

Date of birth: ___ day ___ month ___ year

Are you?

- Full time worker
- Full time athlete
- Full time student
- Part time worker
- Unemployed

If you were employed in the last 4 weeks:

What was/is your principle occupation? _____
 How many hours did you work/ week ___ hours

SECTION 2: ROWING AND SPORT EXPERIENCE

1) At what age did you first get involved in organised rowing?

- Less than 10 years
- Age 10-11
- Age 12-13
- Age 14-15
- Age 15-17
- Age 18-19
- 20 yrs or older

2) At what level did you row last season? (Tick one)

- | | |
|---|---------------------------------------|
| Senior international <input type="checkbox"/> | Junior <input type="checkbox"/> |
| U-23 international <input type="checkbox"/> | Novice <input type="checkbox"/> |
| Junior international <input type="checkbox"/> | Intermediate <input type="checkbox"/> |
| Senior <input type="checkbox"/> | |

3) At what level do you intend to row this season?

Senior international
U-23 international
Junior international
Senior

Junior
Novice
Intermediate

4) What is the *highest level of competition* at which you have rowed?

Olympic Games
Senior world championships
Senior world cup regatta
U23 world championships
Junior world championships
Coupe Des Jeunesse
Home countries
Irish Championships
Other (please state) _____

5) In what type of rowing are you involved?

Sweep
Sculling
Both

6) If you are a sweep rower, on what side do you row?

Bow
Stroke
Both

7) Are you

Lightweight?
Heavyweight?

8) In what type of boat did you do most of your training last season?

1x 2- 2+
2x 4- 4+
4x 8+

9) Did you miss any training last season?

Yes number of weeks missed _____ weeks
No (*go to question 11*)

10) How many of these weeks missed were due to injury?

_____ weeks

11) Is rowing your main sport?

Yes (*go to section 3*) No

12) If not what is your major sport

ID for office use only

SECTION 3: TRAINING / EQUIPMENT

NOTE: For the purposes of this section, the following definitions may apply;

- **Strength training** – involves a session to increase power such as weight training.
- **Endurance training** – involves a session to improve stamina, such as long slow distance pieces.
- **Interval** – is a session with repeated fast-paced bouts of exercise with rests in between and would include a session such as 500m pieces or '17 on, 5 off' in the boat.
- **Flexibility** – is usually a stretching session.
- **Core stability** – is a session specifically designed to strengthen the abdominal and back (trunk) muscles.

TRAINING

1) When did you compete in your last race last season

- August
- July
- June
- May
- April
- Pre-April

2) Have you done any training since the end of last season?

- Yes No

3) When did you start your pre (off) season training?

| | June Or before | July | August | September | October |
|----------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Strength | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Endurance | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Interval | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Flexibility | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Core stability | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

4) On average, how many times a week did you train in the off-season?

| | Once or less | 2-3 times | 4-5 times | 6 times | 7 times or more |
|----------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Strength | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Endurance | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Interval | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Flexibility | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Core stability | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

5) On average, how long did you train in each training session?

| | Less than 20 min | 20-39 min | 40-59 min | 60-89 min | 90 min or more |
|----------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Strength | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Endurance | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Interval | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Flexibility | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Core stability | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

6) On average, how hard did you train each session?

| | Not hard at all | moderately hard | very hard |
|----------------|--------------------------|--------------------------|--------------------------|
| Strength | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Endurance | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Interval | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Flexibility | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Core stability | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

7) What were you trying to accomplish through your off-season training? (Tick all that are applicable)

- | | | | | | |
|--------------------|---|-------------|--------------------------|-------------|--------------------------|
| Endurance/ stamina | <input type="checkbox"/> | Strength | <input type="checkbox"/> | Flexibility | <input type="checkbox"/> |
| Speed | <input type="checkbox"/> | Weight gain | <input type="checkbox"/> | Weight loss | <input type="checkbox"/> |
| Other | <input type="checkbox"/> (please state) _____ | | | | |

8) Who developed your off-season training programme?

- Didn't have one
- Me
- Coach
- Other (please state) _____

9) What was your main off-season activity/ sport?

- Rowing
- Ergometer
- Running
- Cycling
- Other (please state) _____

WARM-UP PATTERNS

1) In your last season did you warm-up before:

| | Never | Rarely | About ½ The time | Often | Always |
|-------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Training | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Competition | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

2) In your last season, how long did you usually spend warming up before:

| | Less than 5 min | 5-14 min | 15-29 min | 30-45 mins | 45 min+ |
|-------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Training | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Competition | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

3) In your last season did you immediately warm down following competition?

Yes No

4) If yes, please describe your warm down procedure:

SECTION 4: INJURY EXPERIENCE

NOTE:

For the purposes of this project you may define an injury as a problem, which causes you to miss:

- *At least one competition (regatta, head or trial) OR*
- *At least 2 training sessions OR*
- *Required at least one visit to a health professional for treatment*

1) Rowing or rowing training related injury –please tick any that you have had in the last 12 months:

| | | | | | |
|------------|--------------------------|----------------|--------------------------|----------------|--------------------------|
| Lower back | <input type="checkbox"/> | Mid/upper back | <input type="checkbox"/> | Neck | <input type="checkbox"/> |
| Shoulder | <input type="checkbox"/> | Upper arm | <input type="checkbox"/> | Elbow | <input type="checkbox"/> |
| Forearm | <input type="checkbox"/> | Wrist/hand | <input type="checkbox"/> | Hip | <input type="checkbox"/> |
| Thigh | <input type="checkbox"/> | Knee | <input type="checkbox"/> | Lower leg | <input type="checkbox"/> |
| Ankle | <input type="checkbox"/> | Foot | <input type="checkbox"/> | Chest (or rib) | <input type="checkbox"/> |

Other (please describe) _____

2) Other injury –please detail any non-rowing related injury you have had in the Last 12 months:

3) Do you have any injuries now that affect your ability to train for rowing?

Yes No

3a) If yes, please describe:

4) Did you have an injury during the rowing season last year that caused you either miss at least one regatta or end your season early?

Yes No

5) Have you had any injuries since the end of last season?

Yes No

Have not been training since

6) Have you ever trained against medical or a physiotherapist's advice?

Yes No

7) Do you have any difficulties obtaining treatment for you injuries?

Yes No

8) If yes, why?

- Too expensive
- Inconvenient
- No access to practitioner
- Other (please state) _____

9) Who would you generally approach for treatment of an injury?

- Physiotherapist
- Doctor
- Osteopath
- Chiropractor
- Massage therapist
- Trainer
- Coach
- Other (please state) _____

Comments

Thank-you for your time.

Reference:

Waller AE, Feehan M, Marshall SW, Chalmers DJ. The New Zealand Rugby Injury and performance project: 1. Design and methodology of a prospective follow-up study. *British Journal Of Sports Medicine*, 1994; 28(4), 223-228.

APPENDIX B

MONTHLY ATHLETE INTERVIEW, STUDY 1.

Athlete ID number

Month ending _____

SECTION 1 – ROWING EXPERIENCE

1) Have you been training this month? Yes No (go to section 2)

2) Have you competed this month? Yes No (go to question 6)

3) In how many races have you competed this month?

| | | | | |
|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| 1-2 | 3-4 | 5-6 | 7-8 | 9-10 |
| <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 10-11 | 12-13 | 14-15 | 16-17 | 18 times or more |
| <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

4) Were any of these races trials? Yes No (go to question)

5) Please state purpose of trials

6) Have you been required to make weight this month?

No Yes _____ KG

7) On average, how many times a week did you train this month?

| | Once or less | 2-3 times | 4-5 times | 6 times | 7 times or more |
|----------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Strength | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Endurance | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Interval | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Flexibility | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Core stability | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

8) On average, how long did you train in each training session?

| | Less than 20 min | 20-39 min | 40-59 min | 60-89 min | 90 min or more |
|----------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Strength | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Endurance | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Interval | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Flexibility | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Core stability | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

9) On average, how hard did you train each session?

| | Not hard at all | moderately hard | very hard |
|----------------|--------------------------|--------------------------|--------------------------|
| Strength | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Endurance | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Interval | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Flexibility | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Core stability | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

10) On average, how many times a week did you train this month in each of these areas?

| | | | | | |
|-------------|---|--------------------------|--------------------------|--------------------------|--------------------------|
| | 1-2 times | 3-4 times | 5-6 times | 7-8 times | 9-10 times |
| Boat | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| | 10-11 times | 12-13 times | 14-15 times | 16-17 times | 18 times or more |
| | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| | Did not train in this area <input type="checkbox"/> | | | | |

| | | | | | |
|-------------|---|--------------------------|--------------------------|--------------------------|--------------------------|
| | 1-2 times | 3-4 times | 5-6 times | 7-8 times | 9-10 times |
| Ergo | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| | 10-11 times | 12-13 times | 14-15 times | 16-17 times | 18 times or more |
| | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| | Did not train in this area <input type="checkbox"/> | | | | |

| | | | | | |
|------------------------|---|--------------------------|--------------------------|--------------------------|--------------------------|
| | 1-2 times | 3-4 times | 5-6 times | 7-8 times | 9-10 times |
| Weights (Heavy) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| | 10-11 times | 12-13 times | 14-15 times | 16-17 times | 18 times or more |
| | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| | Did not train in this area <input type="checkbox"/> | | | | |

| | | | | | |
|-------------------------|---|--------------------------|--------------------------|--------------------------|--------------------------|
| | 1-2 times | 3-4 times | 5-6 times | 7-8 times | 9-10 times |
| Weights (endur.) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| | 10-11 times | 12-13 times | 14-15 times | 16-17 times | 18 times or more |
| | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| | Did not train in this area <input type="checkbox"/> | | | | |

| | | | | | |
|---------------------|---|--------------------------|--------------------------|--------------------------|--------------------------|
| | 1-2 times | 3-4 times | 5-6 times | 7-8 times | 9-10 times |
| Land (other) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| | 10-11 times | 12-13 times | 14-15 times | 16-17 times | 18 times or more |
| | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| | Did not train in this area <input type="checkbox"/> | | | | |

| | 1-2 times | 3-4 times | 5-6 times | 7-8 times | 9-10 times |
|---|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Core Stability | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| | 10-11 times | 12-13 times | 14-15 times | 16-17 times | 18 times or more |
| | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Did not train in this area <input type="checkbox"/> | | | | | |

| | 1-2 times | 3-4 times | 5-6 times | 7-8 times | 9-10 times |
|---|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Flexibil. | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| | 10-11 times | 12-13 times | 14-15 times | 16-17 times | 18 times or more |
| | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Did not train in this area <input type="checkbox"/> | | | | | |

11) Please detail any other training that you have done as part of your training for rowing

Running
Cycling
Swimming
Other (please state) _____

12) On average, how long did you warm up

Before water training _____ mins
Before land training _____ mins
Did not warm up _____ mins

13) Did you miss any training over the last month for a reason other than injury?

No (go to section 2)
Yes

14) Did you miss training because of illness?

No
Yes Please specify _____

SECTION 2 – INJURY EXPERIENCE

1) Did you experience any new injuries during training last month?

Yes No

(If yes, write down a description of the events and code the events)

2) Did you experience any new injuries during racing last month?

Yes No

(If yes, write down a description of the events and code the events)

3) Were you injured doing anything else other than rowing or rowing training last month?

Yes No

(If yes, write down a description of the events and code the events)

4) Did you miss any training or racing last month due to that / any of those new injury event(s)?

Yes No

5) Did you receive any medical attention for that / any of those injury events(s)?

Yes No

*** Go to injury forms if injury fits criteria from definition**

6) Have you had any other niggling aches or pains or other physical problems, which interfered with your daily activities last month?

Yes No

Describe _____

7) In the past month did you have any treatment or receive any medical attention for any injury you had previously experienced?

Yes No

7a) in the last month, did you miss any training or racing due to an injury that you had previously experienced?

Yes No

If yes to 7 or 7a:

7b) was this for an injury that you told me about before?

Yes No

If no, fill in an injury form only if the injury occurred after the start of the study.

I yes to medical attention:

What sort of treatment did you get in the past month?

I no to medical attention:

Was there a reason why you did not have treatment?

Who gave this treatment?

Name: _____

Address/Clinic: _____

Interview details

Athlete ID:

1) Day of interview

Monday

Thursday

Sunday

Tuesday

Friday

Wednesday

Saturday

2) Date of interview: _____ day _____ month _____ year.

3) Interview for month number: _____

4) Time interview began: _____: _____ am/pm

5) Time interview finished: _____: _____ am/pm

6) Total interview time: _____ minutes

Monthly injury form

Athlete ID

Month number _____

Event number _____

1) What was the day and time of the injury event?

Day _____ Date: _____ day _____ month _____ year _____ Year _____

2) What were you doing when you were injured?

Training (go to question 3)

Racing (go to question 4)

3) Please specify further

Code:

4) Please further specify the injury mechanism

Code:

5) What parts of your body were injured?

| | | |
|-------------------|------------|------------|
| Orientation _____ | Site _____ | Type _____ |
| Orientation _____ | Site _____ | Type _____ |
| Orientation _____ | Site _____ | Type _____ |
| Orientation _____ | Site _____ | Type _____ |

6) Did you receive any medical attention or treatment for this injury?

No Yes

If yes, what treatment have you had?

Who gave the treatment? Code: if other, please specify _____

Name: _____

Address /clinic: _____

7) Do you plan to seek any further treatment or are you having on-going treatment for this injury?

No Yes

8) How long after you began training or racing were you injured?

_____ Mins

9) Did you continue to train or race after you were injured?

No Yes

10) Did this injury interfere with what you planned to do the following day?

No Yes

11) Have you injured this part of your body before?

No Yes

If yes, did you receive medical treatment for that injury?

No Yes

APPENDIX C

STATIC CALIBRATION OF SPECTROTILT INCLINOMETER, STUDY 2

Report on calibration of the Spectrotilt Electronic Inclinometer for angle measurements.

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Affiliation: ***Centre for Bioengineering***
 Trinity College Dublin

Date: ***May 2005***

Introduction

The Spectrotilt RS232 Electronic Inclinometer (Spectron Systems Technology Inc. New York, USA) is a cheap and lightweight angular displacement measurement device, with the key advantage that it does not require a fixed rotation axis between the moving body and the frame of reference. However, since the device involves settling of a fluid in a tube, application of the device is limited under certain dynamic conditions. The reported settling time for the device is 300 ms as per the manufacturer's specifications, and therefore it is unclear a priori whether the device is suitable for frontal plane lumbar spine angular measurements during rowing.

This report details derivation of the calibration constant for the Spectrotilt Inclinometer, and an assessment of the dynamic response of the sensor as a function of frequency. In particular, the response of the sensor over the range of expected frequencies during rowing is analyzed.

Static Calibration of Spectrotilt Inclinometer

Static calibration was performed using a Radionics rotational potentiometer connected into a simple pendulum system with a protractor. The Spectrotilt Inclinometer was rigidly fixed to the pendulum, which was then fixed at a variety of different angles at which measurements were taken using the Biometrics DataLog. A Matlab script was used to calculate the number of bits per degree for the potentiometer and the Spectrotilt Inclinometer respectively for different orientations of the pendulum, see table 1 below. The results show an average of 8.19 bits per degree for the potentiometer (standard deviation 0.35) and 21.55 bits per degree for the inclinometer (standard deviation 0.81). A calibration constant for the inclinometer of 21.55 bits per degree was therefore employed for all experimental work.

| Test descriptor | Start position (degrees) | End position (degrees) | Potentiometer (bits per degree) | Inclinometer (bits per degree) |
|-----------------|--------------------------|------------------------|---------------------------------|--------------------------------|
| Feb24/2 | 0 | 30 | 8.26 | 21.69 |
| | 0 | 20 | 8.23 | 21.35 |
| | 0 | 10 | 8.76 | 22.77 |
| Feb24/1 | 0 | 30 | 8.17 | 21.58 |
| | 0 | 15 | 7.75 | 21.05 |
| | 15 | 30 | 8.59 | 21.11 |
| Feb24/2 | 10 | 20 | 7.70 | 19.95 |
| | 20 | 30 | 8.31 | 22.35 |
| | 10 | 30 | 8.00 | 21.16 |
| | | | 8.19 (0.35) | 21.55 (0.81) |

Table 1. Static pendulum calibration tests

Dynamic Performance of Spectrotilt Inclinometer

The Spectrotilt Datasheet reports a settling time of 300ms for the inclinometer. It was therefore not clear whether the dynamic response of this sensor is adequate for the rowing application intended. In order to determine this, an experimental procedure using a four bar crank rocker mechanism was devised. During the intended rowing measurements, the lower back of the rower rotates in a rocking matter in the frontal plane to maintain balance of the boat. The maximum rotation either side of the vertical was estimated to be 20°. The four-bar crank rocker linkage is driven by an electric motor and designed so that the rocker rotates almost 20° either side of its vertical (neutral) position, see figure 1. The input

current to the electric motor was variable, and therefore the frequency of the rocking motion could be controlled. The inclinometer was rigidly connected to the rocker bar, and the rotational potentiometer was connected across the joint connecting the rocker link to the frame. In this way, the response of the inclinometer over a range of frequencies could be compared to the potentiometer measurement, and an understanding of the ability of the inclinometer to measure dynamic angle changes was assessed.

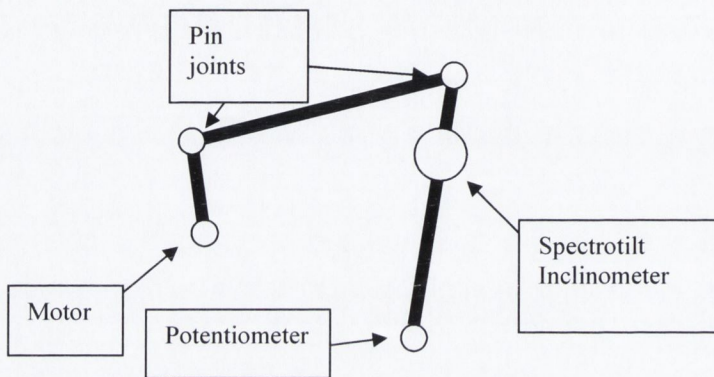


Figure 1: Four bar crank rocker rig for inclinometer testing

Two separate tests were performed, in which the motor/rocker speed was varied, and the data was stored in files named files four_bar_data1.txt and four_bar_data2.txt. Using a Matlab script (see end of report), the following sets of comparative graphs were constructed, see figures 2 & 3.

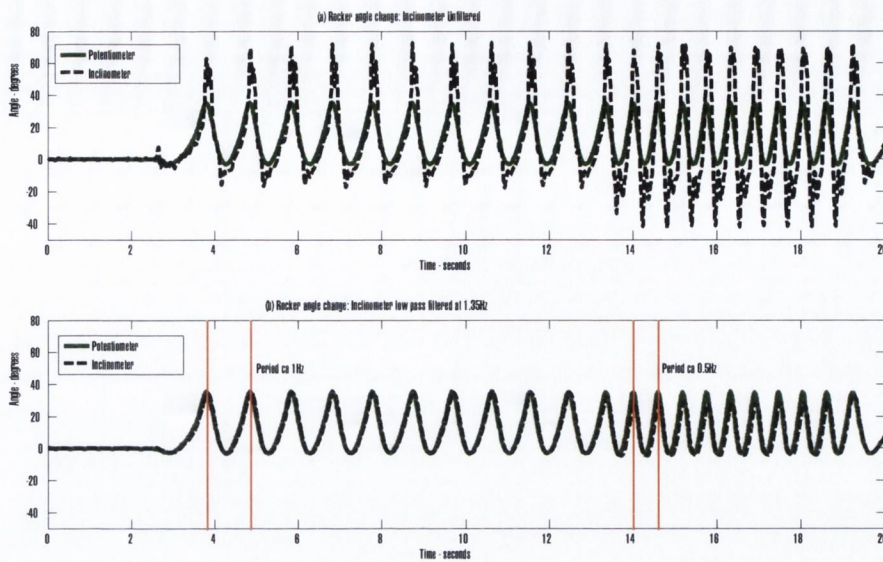


Figure 2: Results of four_bar_data1 comparison between inclinometer and potentiometer: (a) inclinometer unfiltered and (b) inclinometer filtered.

In the test, the rocker was held at a constant angle for nearly the first 3 seconds, after which it oscillated almost 40° to the left and back to a neutral position with a period of approximately 1Hz, and this was continued until about 14 seconds, when the period of the oscillation was reduced to about 0.5Hz. The rotational potentiometer has a very good dynamic response, and can be considered as the gold standard for assessment of the inclinometer response. The raw (unfiltered) inclinometer response is shown above in figure 2a. It can be seen that the magnitude of the inclinometer angular predictions is substantially greater than for the potentiometer, and the dynamic nature of the rocker motion has introduced some higher frequency noise into the response.

In consequence, a digital low pass Butterworth filter was applied, and testing of different cut off frequencies revealed that a cut off frequency of 1.35 Hz resulted in a very close match between the inclinometer angular predictions and the potentiometer angular measurements when the rocker frequency is of the order of 1 Hz or less (see figure 2b). Analysis of differences between the potentiometer and inclinometer peak predictions in the steady state region between 5 and 14 seconds showed the following:

| | |
|---------------------------|-----------------|
| Mean peaks difference | = -0.19 degrees |
| Standard peaks difference | = 0.15 degrees |
| Max peaks difference | = 0.38 degrees |

In contrast, for higher frequency motions of 2 Hz, large discrepancies between inclinometer angle predictions of the potentiometer reading result see figure 2b. When the movement is not strictly periodic, the comparison is still very good when the frequency of the motion does not exceed 1Hz, see figure 3. These movements were achieved by disconnecting the motor and oscillating the rocker manually.

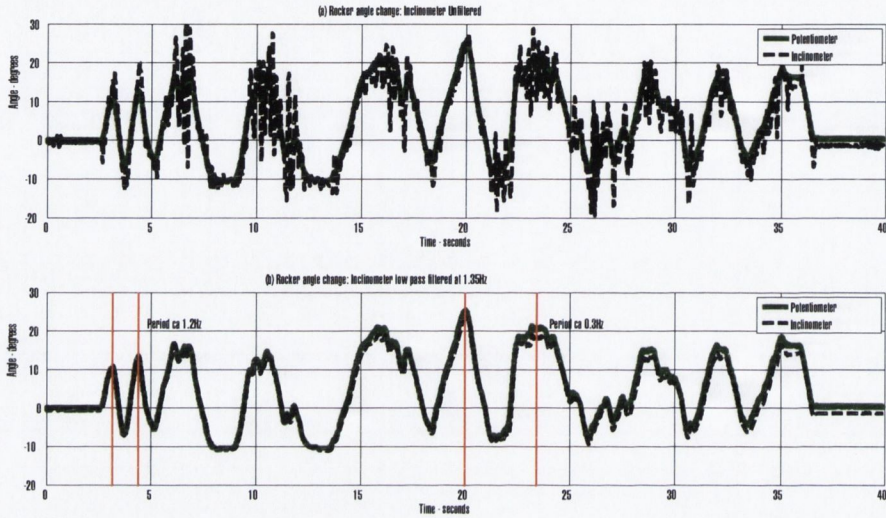


Figure 3: Potentiometer and inclinometer response for non periodic motion: (a) unfiltered inclinometer and (b) filtered inclinometer.

Conclusions

The Spectrotilt Electronic Inclinometer sensor is suitable for measurement of rowing motion with a frequency of up to 1Hz when a low pass filter of 1.35 Hz is applied. Within these limits the maximum error appears to be of the order of 0.5 degrees, and the qualitative motion is very well captured. At higher frequencies, comparative work is still possible, but the calculation of the angle is less accurate in absolute terms.

Matlab script

```
%rowing rig calibration
%close all figures, clear all variables
close all; clear

[filename] = uigetfile('*.txt','*.*');
```

```

no_of_channels = input('please input number of channels recorded (i.e. 1
or 2) ');
fid=fopen(filename,'r');
end_of_file = 0; line_number = 0;

while ~(end_of_file)

    remainder = 'some arbitrary non empty characters';
    line1 = fgets(fid);
    line_number = line_number + 1;

    if feof(fid);          end_of_file = 1;      end;

        [token] = strtok(line1,' ');
        token1 = deblank(token);

        token2 = str2num(token1);

        if (length(token2)~=0)&((length(token2)>=no_of_channels))
            new_file(line_number, 1:no_of_channels) =
token2(1:no_of_channels);
        else
            end_of_file = 1;
        end
end

%do the conversion to required units

sample_rate = 200;

t = 1:length(new_file);
t = t/sample_rate;

%these are average values measured see clino_calib_march04 directory: see
handwritten sheet in folder
mean_pot_bits_per_degree = 8.19;
mean_inc_bits_per_degree = 21.55;

pot_bits = new_file(:,1);

```

```

inc_bits = new_file(:,2);

%for this to work, there has to be a proper rest period of at least a
quarter of a second prior to test
pot_bits_offset = mean(pot_bits(1:50));
inc_bits_offset = mean(inc_bits(1:50));

pot_degrees_change          =          (pot_bits
pot_bits_offset)/mean_pot_bits_per_degree;
inc_degrees_change          =          (inc_bits
inc_bits_offset)/mean_inc_bits_per_degree;

% get butterworth filter coefficients
cutoff = input('lowpass filter cutoff in Hz (1.35 seems to work best...)
');
cutoffa = cutoff/100;
[b,a] = butter(1,cutoffa);
%filter the inclinometer data
inc_degrees_changef = filtfilt(b,a,inc_degrees_change);

ftsize= 16;

figure(1);
subplot(2,1,1)
hold on; grid on; box on;
set(gcf,'color','white')
h11 = plot(t,pot_degrees_change,'-','linewidth',4)
h12 = plot(t,inc_degrees_change,'--','linewidth',3)
set(h12,'color',[ 0 0 0] )
set(h11,'color',[ 0.0 0.4 0.0] )
legend('Potentiometer', 'Inclinometer');
set(legend,'fontsize',ftsize)
title('(a)          Rocker          angle          change:          Inclinometer
Unfiltered','fontsize',ftsize);xlabel('time
seconds','fontsize',ftsize);ylabel('angle - degrees','fontsize',ftsize)
set(gca,'fontsize',ftsize)
axis([ 0 20 -50 80] )

subplot(2,1,2)
hold on; grid on; box on;
set(gcf,'color','white')
h21 = plot(t,pot_degrees_change,'-','linewidth',4)

```

```

h22 = plot(t,inc_degrees_change,'--','linewidth',3)
set(h22,'color',[0 0 0])
set(h21,'color',[0.0 0.4 0.0])
legend('Potentiometer', 'Inclinometer');
set(legend,'fontsize',ftsize)
string = ['(b) Rocker angle change: Inclinometer low pass filtered at
',num2str(cutoff),'Hz'];
title(string,'fontsize',ftsize);                                xlabel('time -
seconds','fontsize',ftsize); ylabel('angle - degrees','fontsize',ftsize);
set(gca,'fontsize',ftsize)
axis([0 20 -50 80])

%comment for random move1 file
plot([3.8191 3.8191],[-60 80],'r','linewidth',2)
plot([4.8560 4.8560],[-60 80],'r-','linewidth',2)
plot([14.0 14.0],[-60 80],'r-','linewidth',2)
plot([14.6025 14.6025],[-60 80],'r-','linewidth',2)
plot([28.70 28.70],[-60 80],'r-','linewidth',2)
plot([29.7408 29.7408],[-60 80],'r-','linewidth',2)
text(5,50,'Period ca 1Hz','fontsize',ftsize);
text(14.7,50,'Period ca 0.5Hz','fontsize',ftsize);

```


APPENDIX D

FISA RULES OF RACING, PART IV, BOATS AND CONSTRUCTION.

(WWW.WORLDRROWING.COM)

Part IV – Boats and construction.

Rule 33 – Free Construction

Requirements for racing boats and equipment:

Boat length

- 1) Maximum length – 11.9m
- 2) Minimum length – 7.2m.

Oar Blade thickness

Oar blades may not be less than 5mm thick for sweep oars and 3mm thick for sculls.

Rule 34 – Boat weights

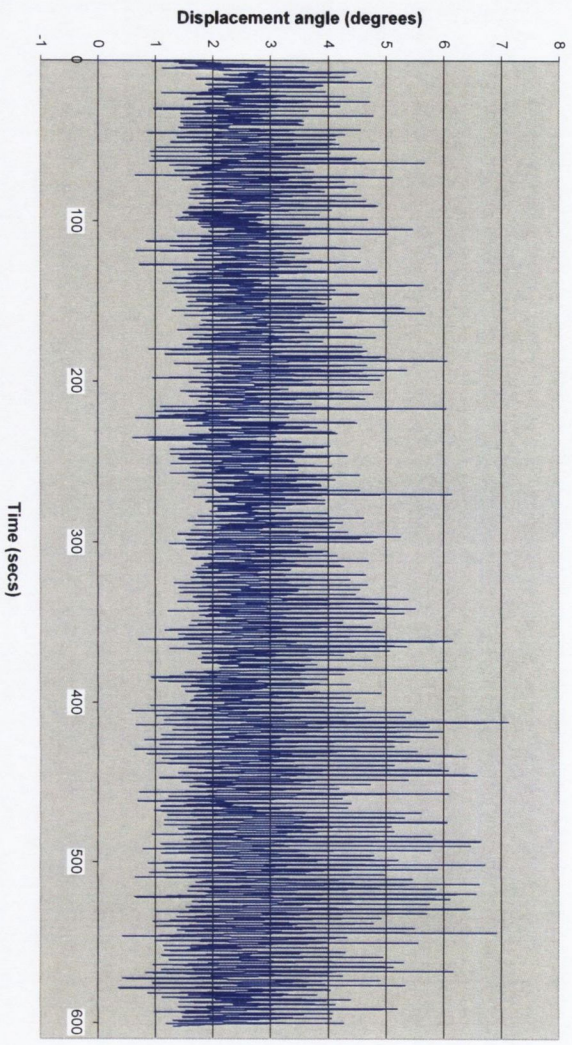
The minimum weight of a single scull should be 14Kg which does not include the oars.’

(Adapted from FISA Rules of Racing and Related Bye – Laws, www.worldrowing.com)

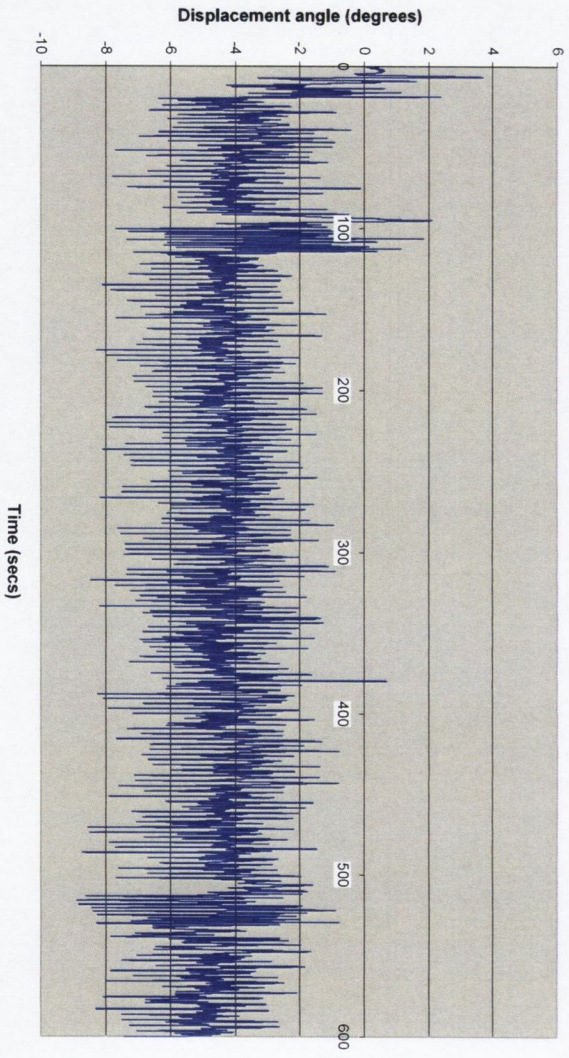
APPENDIX E

ERGOMETER AND BOAT GRAPHS, STUDY 2.

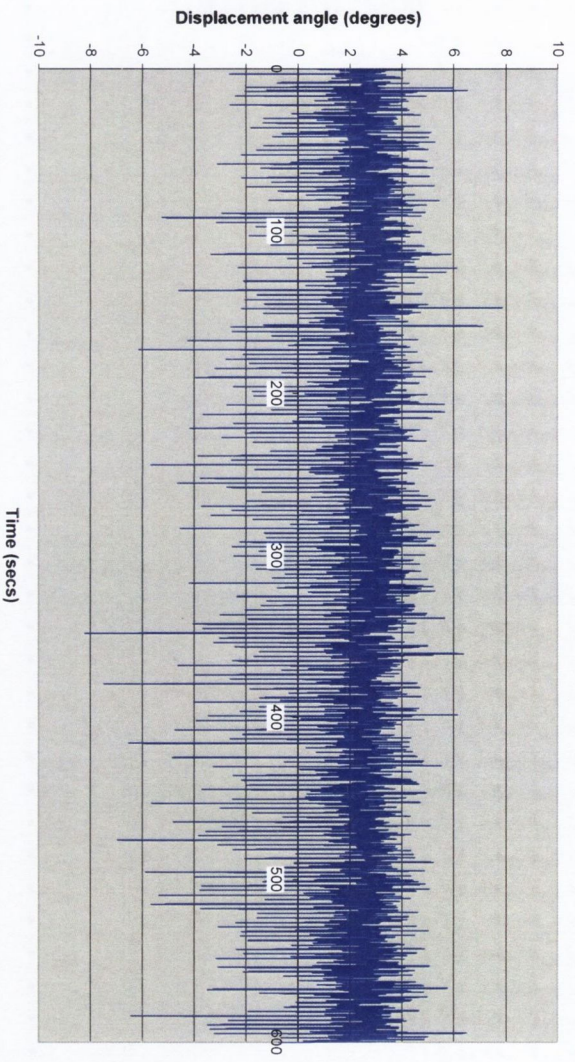
Subject 1: Ergometer



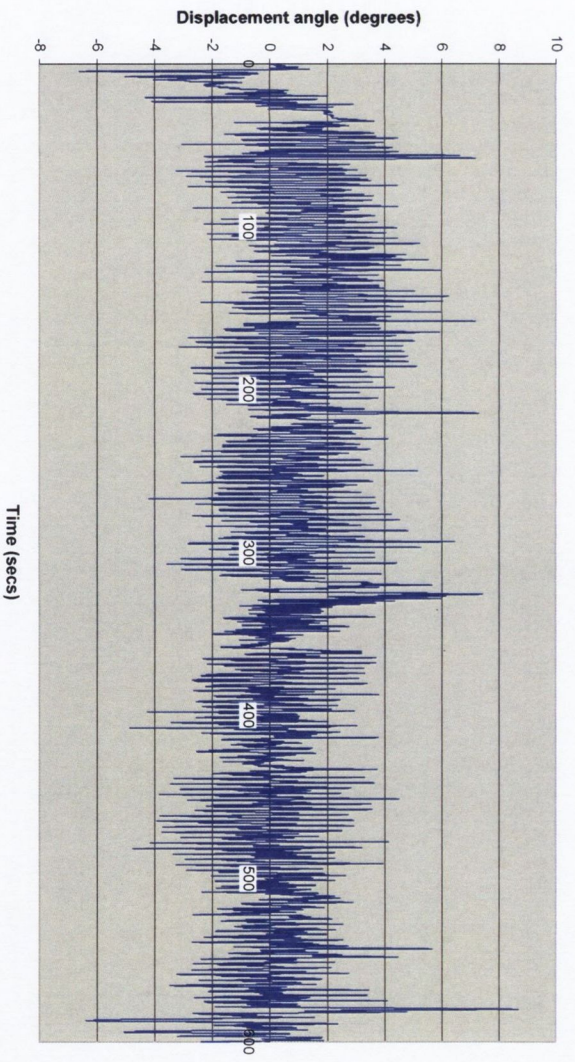
Subject 1: Boat



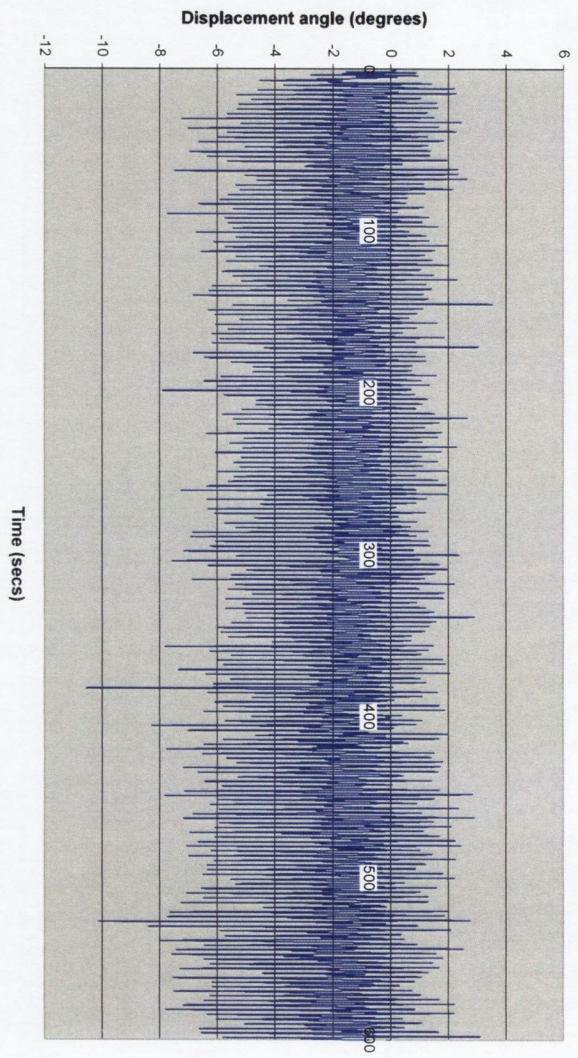
Subject 2: Ergometer



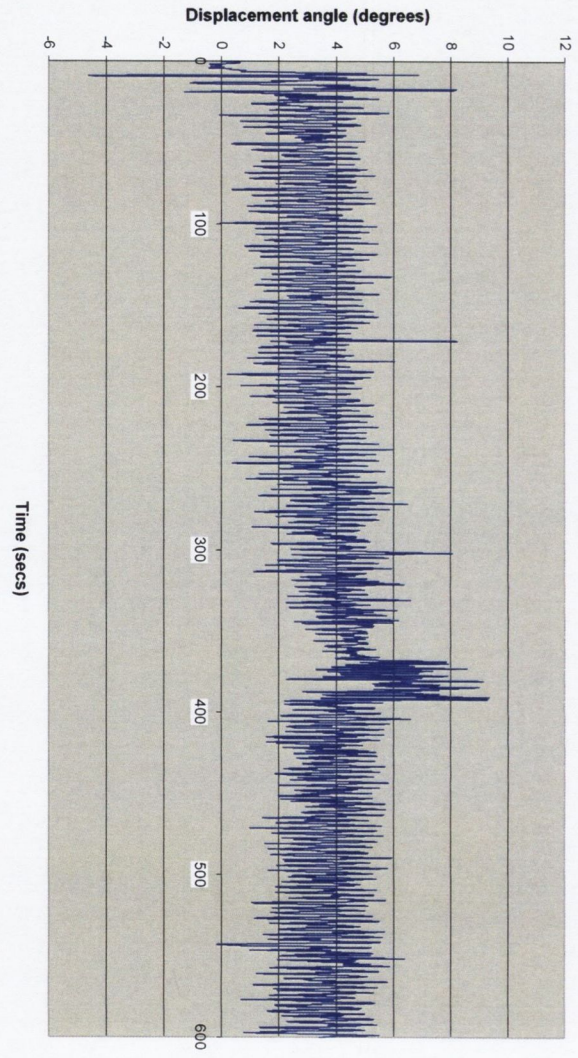
Subject 2: Boat

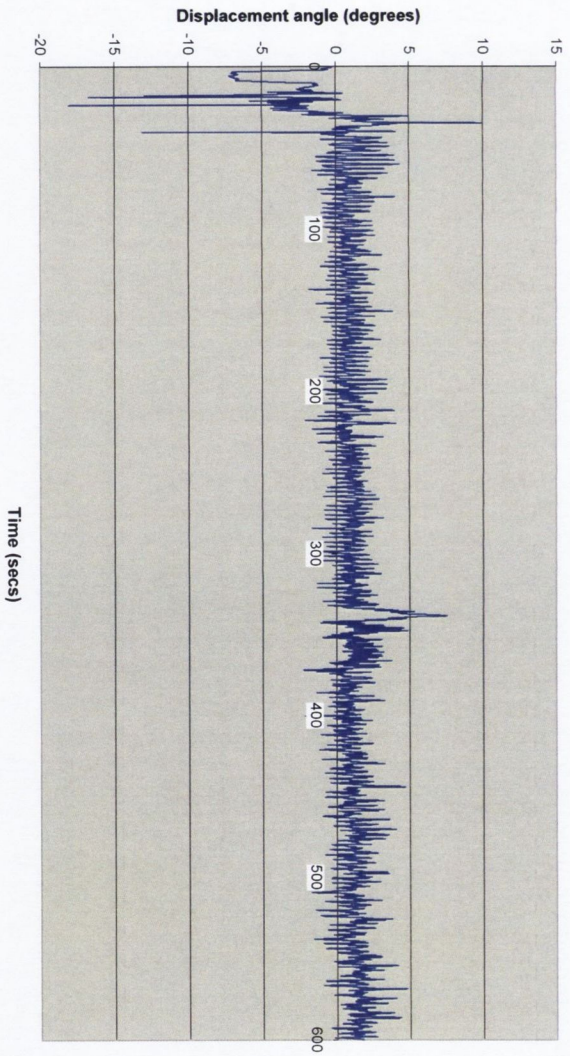
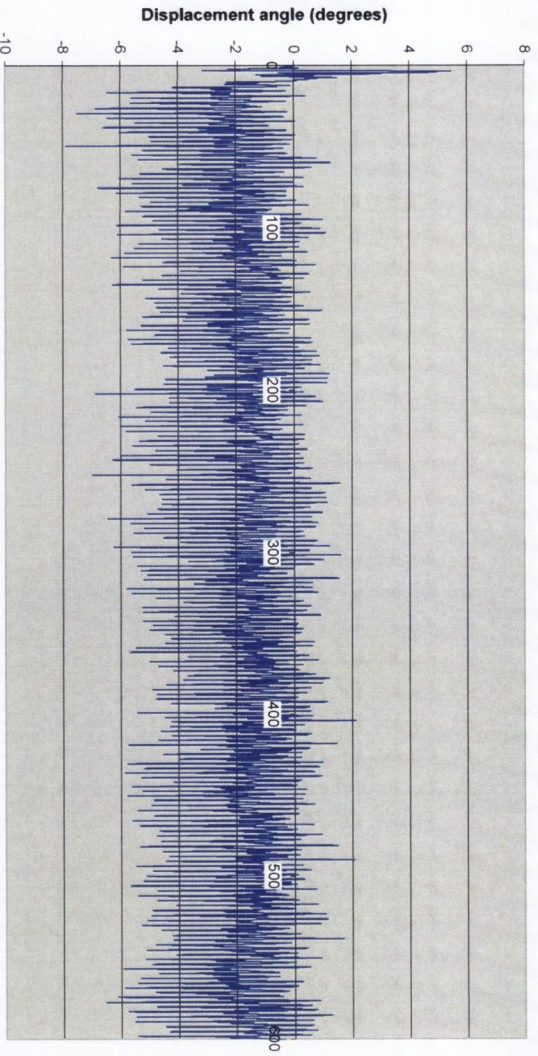


Subject 3: Ergometer

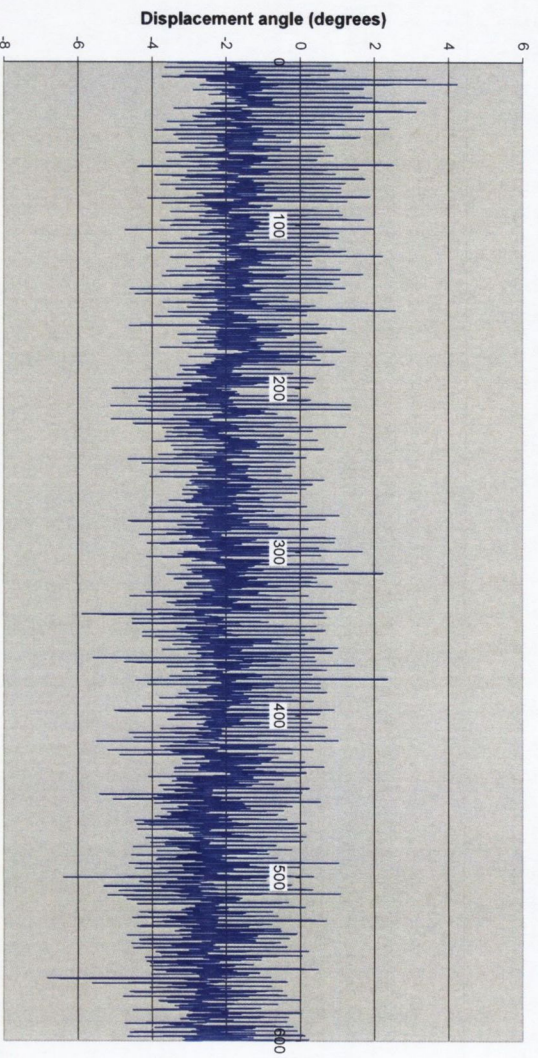


Subject 3: Boat

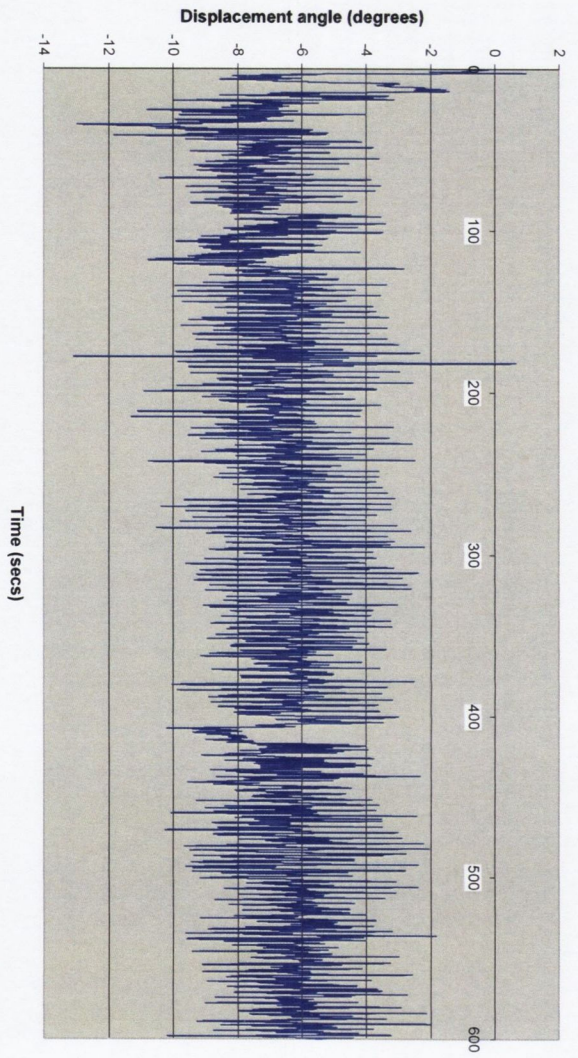




Subject 5: Ergometer

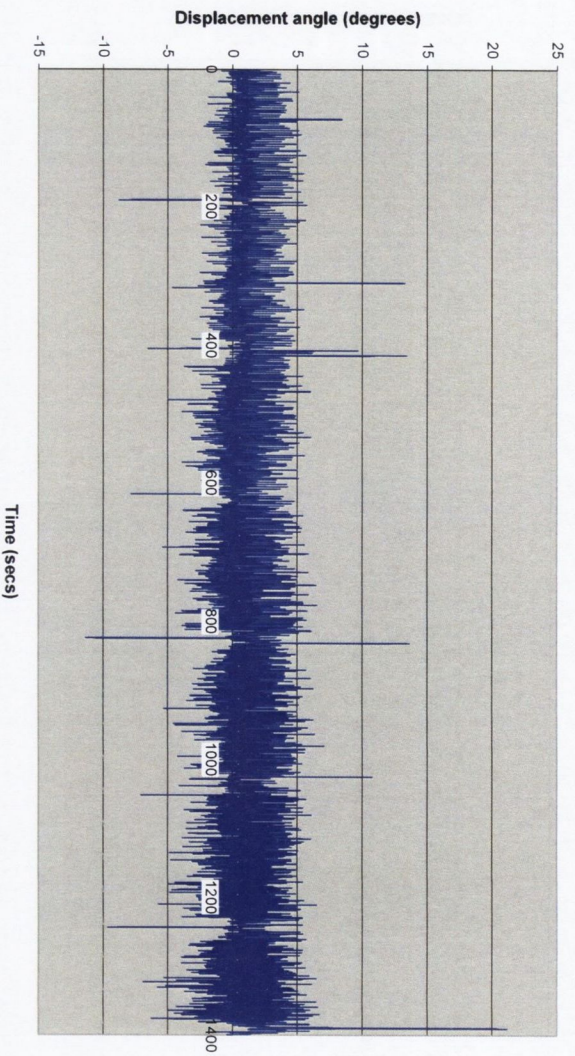


Subject 5: Boat

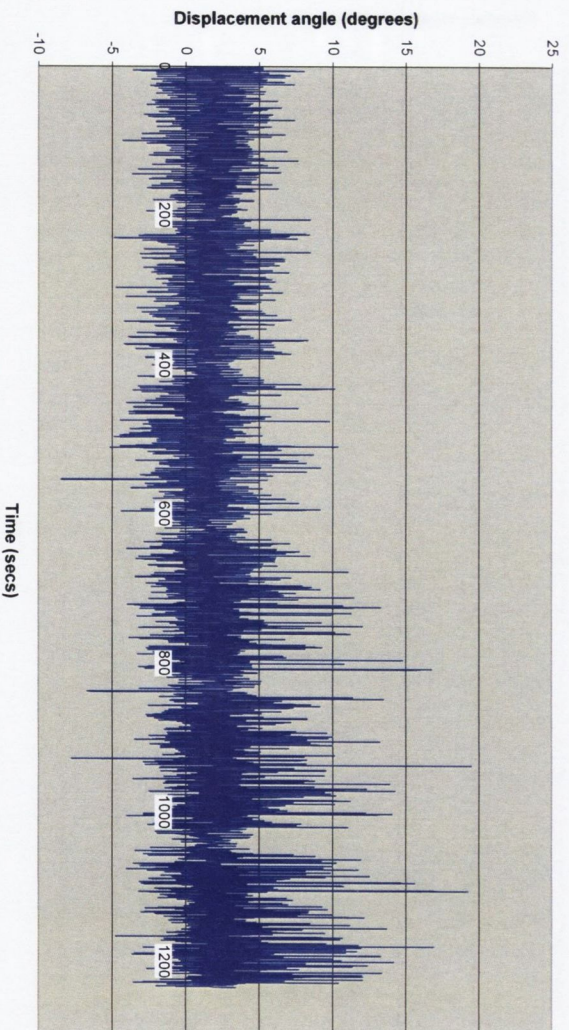


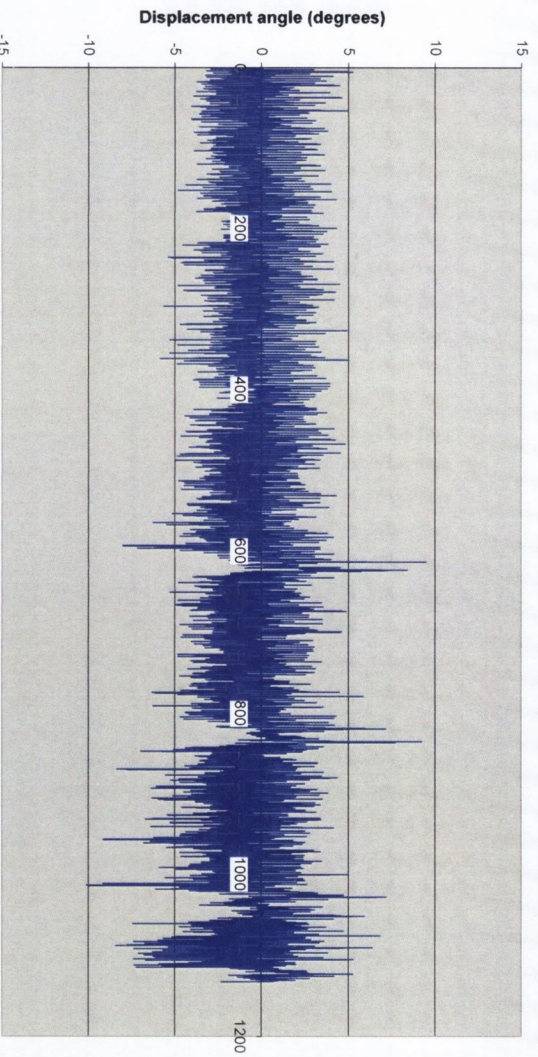
***APPENDIX F:
ERGOMETER GRAPHS, STUDY 3.***

Subject 1: Step test

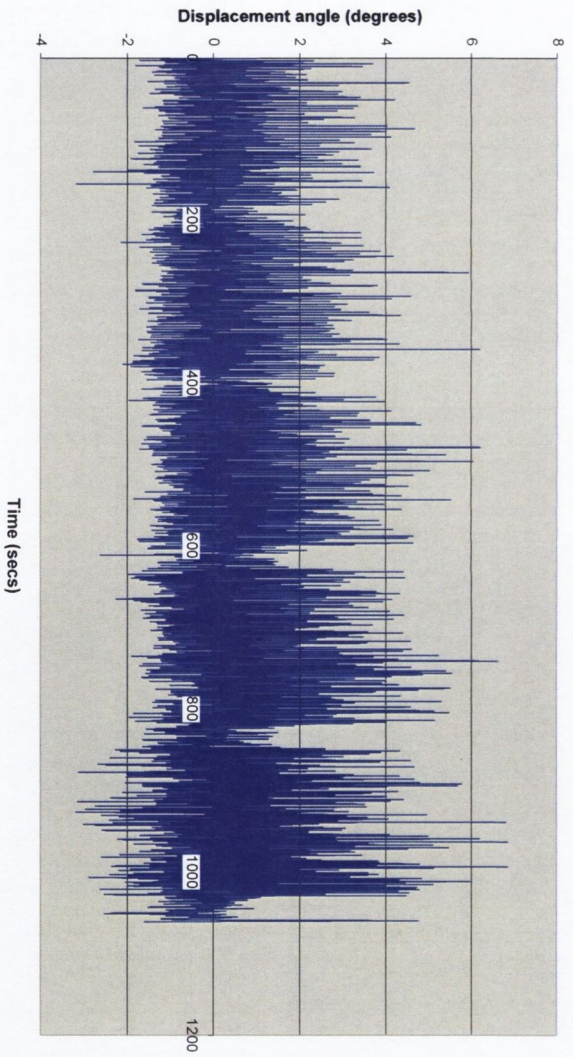


Subject 2: Step test





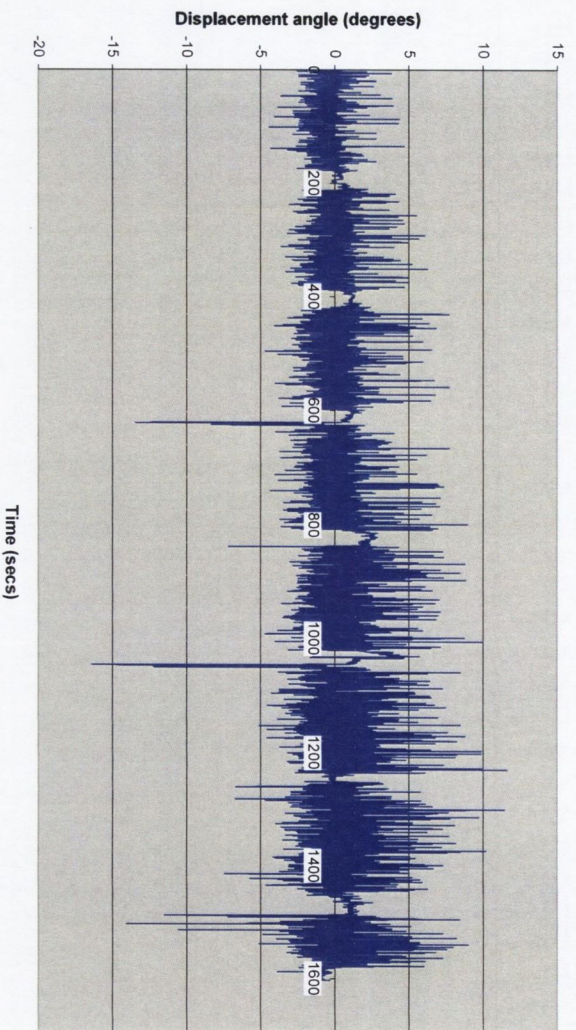
Subject 4: Step test



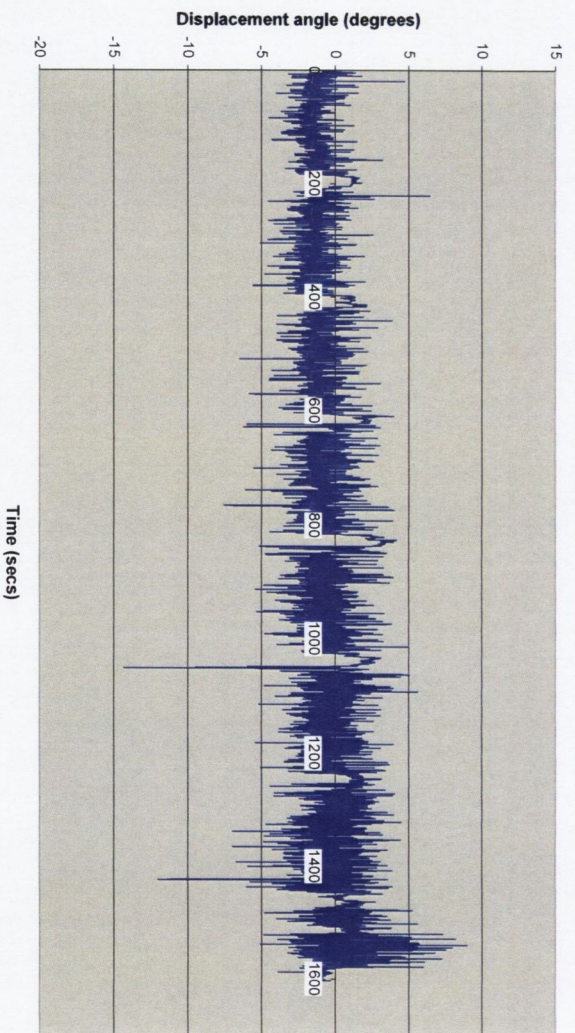
APPENDIX G

ERGOMETER GRAPHS STUDY 4.

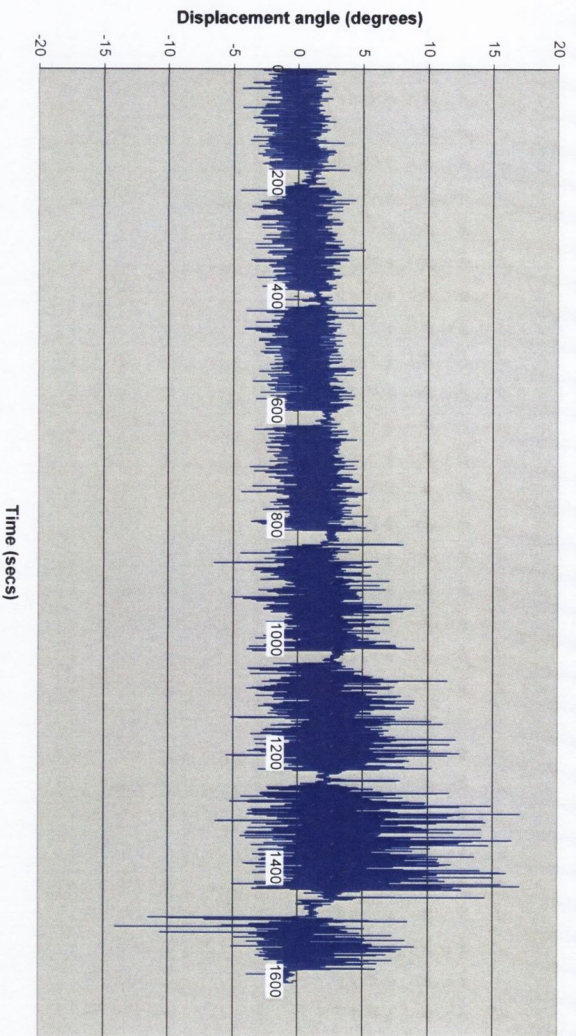
Subject 1 : Step test with bla



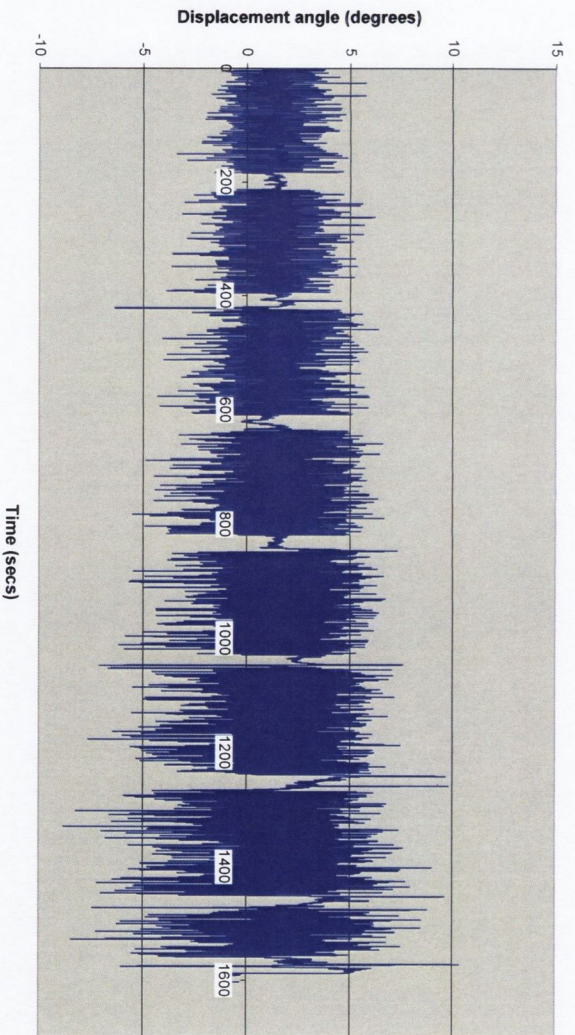
Subject 2: Step test with bla



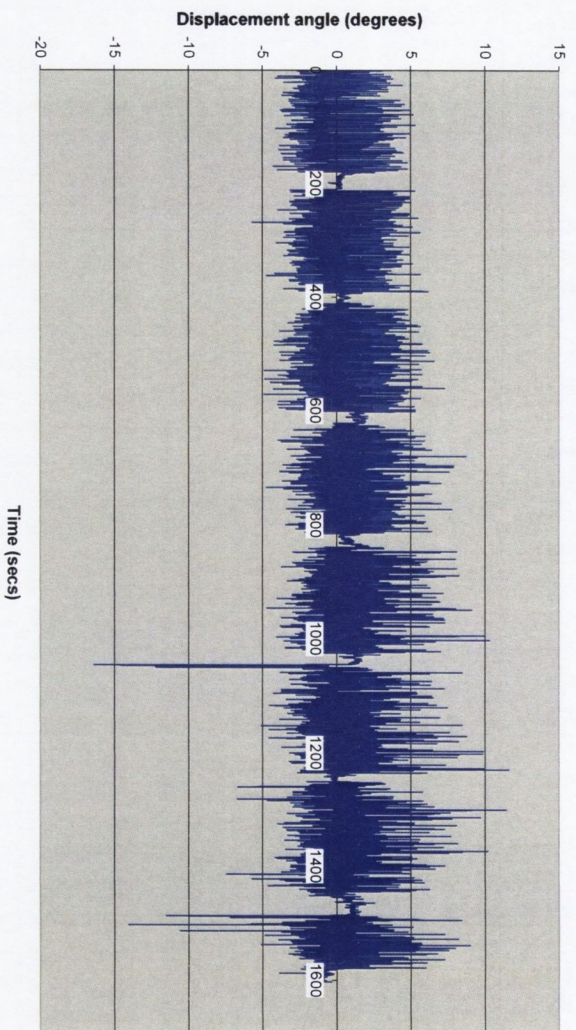
Subject 3: Step test with bla



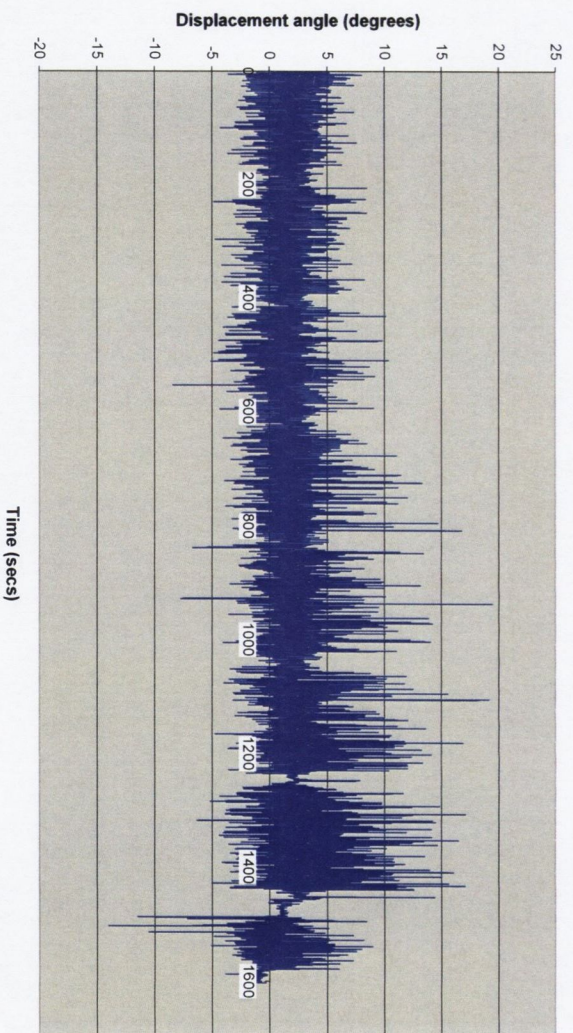
Subject 4: Step test with bla



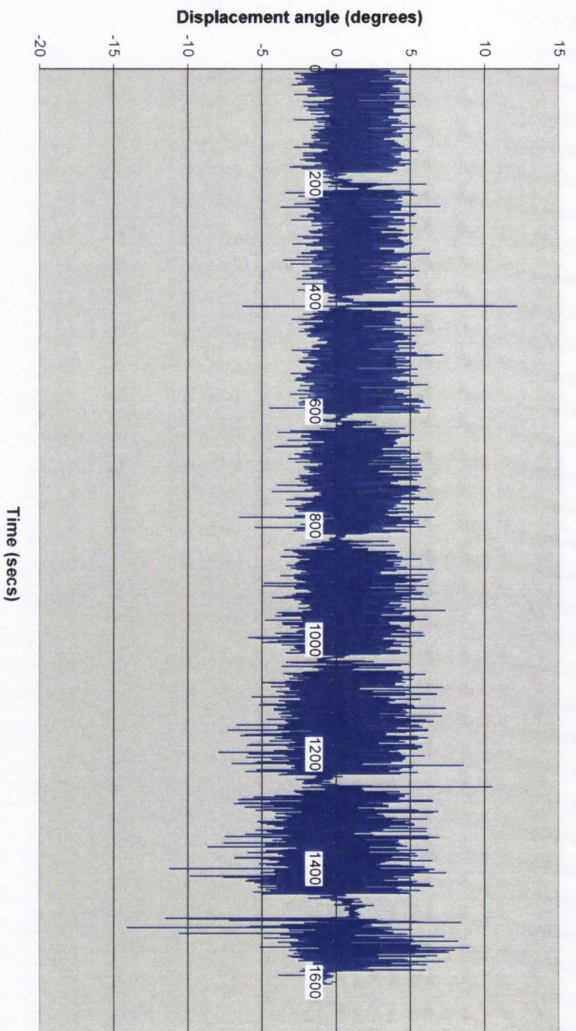
Subject 5: Step test with bla



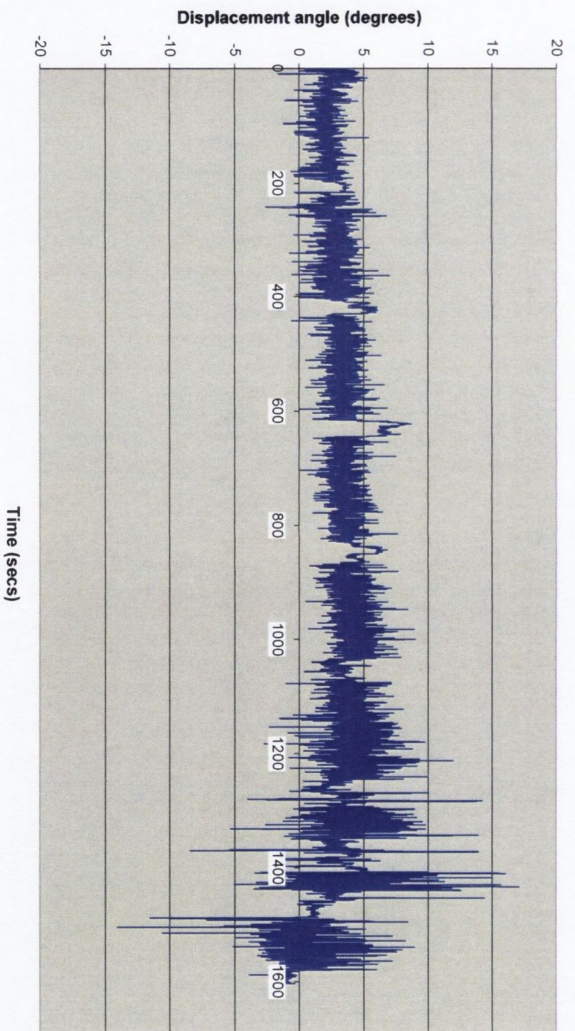
Subject 6: Step test with bla



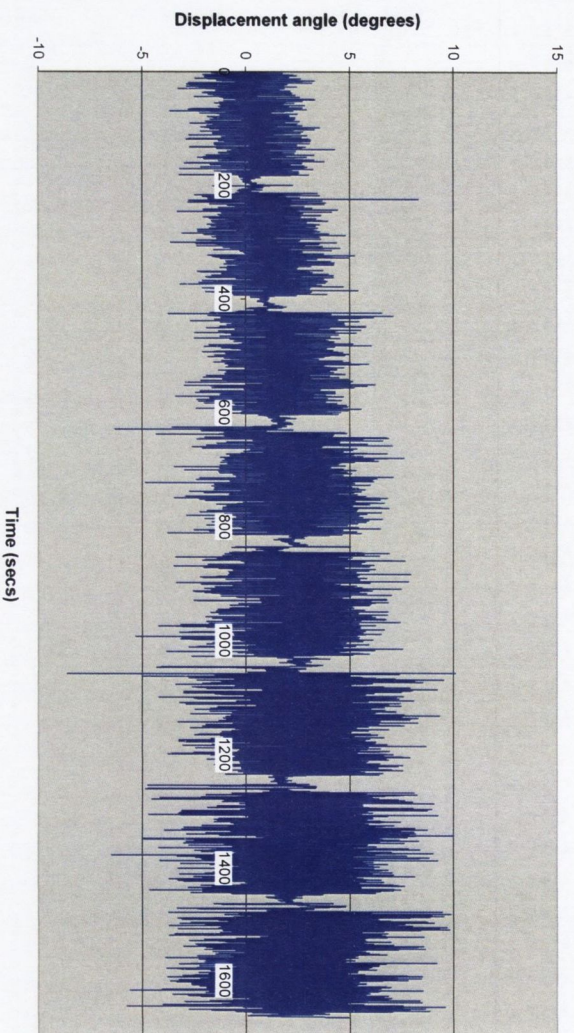
Subject 7: Step test with bla



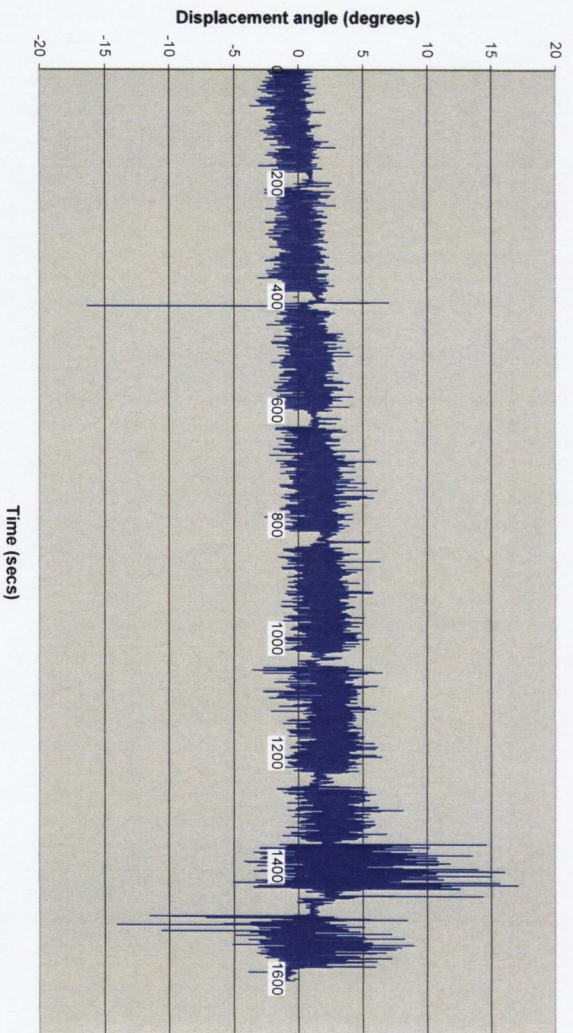
Subject 8: Step test with bla



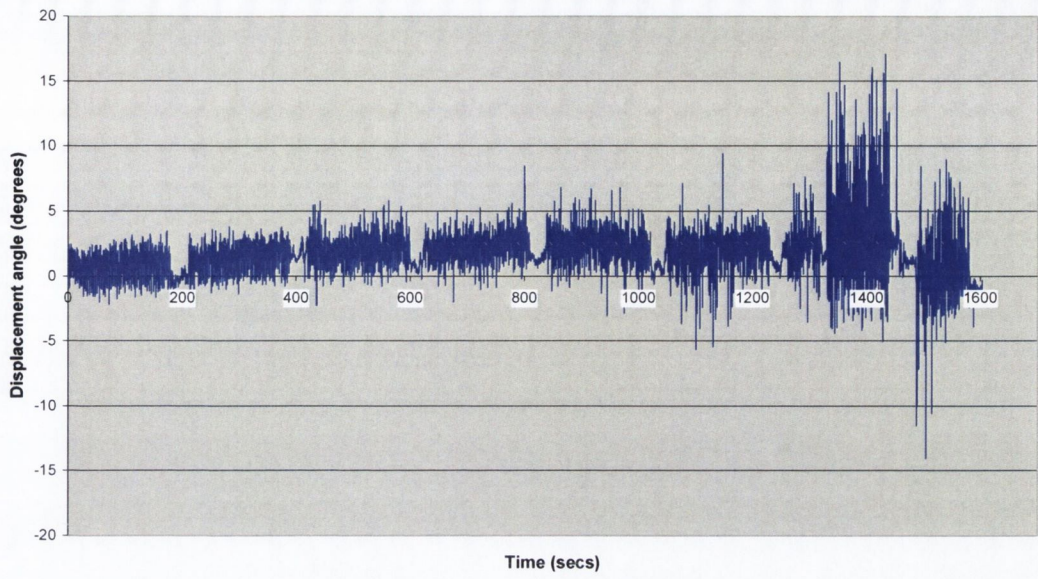
Subject 9: Step test with bla



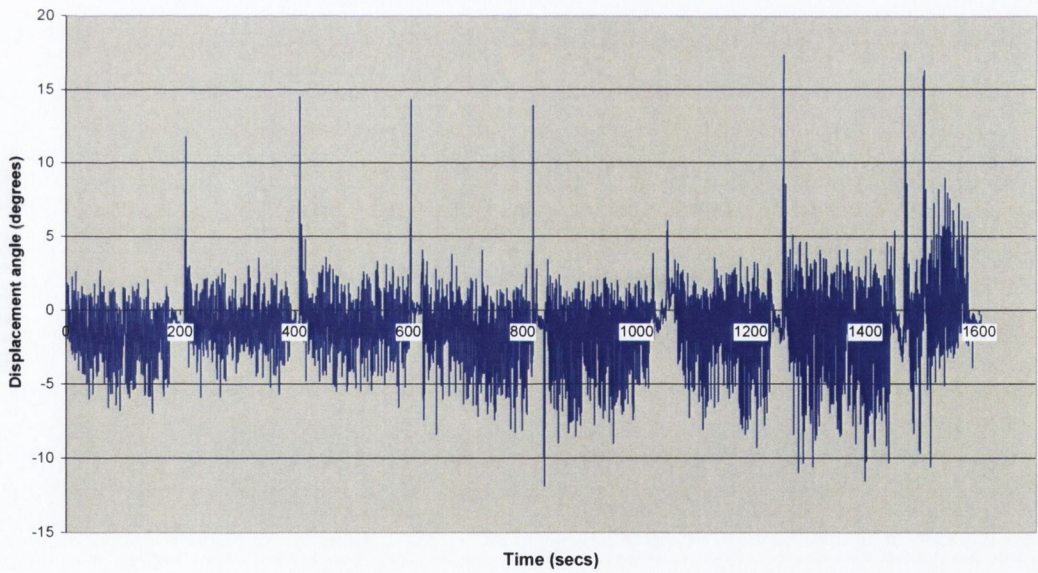
Subject 10: Step test with bla



Subject 11: Step test with bLa



Subject 12: Step test with bLa



*APPENDIX H,
CALIBRATION OF THE ELECTROGONIOMETER, STUDY 5.*

Calibration of the Biometrics EGM against the Universal Goniometer.

Method

The EGM (Biometrics Ltd, UK) was calibrated against the Universal Goniometer (UG), (Baseline Diagnostic and Measuring Instruments, EMS, Wantage, UK). The UG was adapted so that its straight, moveable arm was shortened so that it did not interfere with the flexible strain gauge of the EGM as it was moved. The two end blocks of the EGM were taped to the two arms of the UG which was set at the 0°/180° position. The EGM was connected to the Biometrics DataLog and recording commenced. The UG was then moved from 0° to 90°, stopping for 10 seconds at each of the nine 10° until 90° was reached by the UG at which point recording was discontinued. This procedure was repeated three times. Each 10° increment on the UG was compared with the corresponding reading on the EGM. The measurement error of the readings was analysed using the method described by Bland (1995). A one way ANOVA was conducted and the residual mean square was used to calculate the variation that will occur in readings of the EGM.

Results

The results of the three trials are shown below in table 1.

| universal goniometer | electrogoniometer | | | mean |
|----------------------|-------------------|---------|---------|-------------|
| | trial 1 | trial 2 | trial 3 | |
| 0 | 0 | 0 | 0 | 0.0 |
| 10 | 10 | 10 | 10 | 10.0 |
| 20 | 20 | 20 | 20 | 20.0 |
| 30 | 29 | 30 | 30 | 30.0 |
| 40 | 40 | 40 | 40 | 40.0 |
| 50 | 50 | 49 | 50 | 49.7 |
| 60 | 59 | 58 | 60 | 59.0 |
| 70 | 68 | 69 | 68 | 68.3 |
| 80 | 78 | 78 | 78 | 78.0 |
| 90 | 88 | 89 | 88 | 88.3 |

Table 1: Results of the EGM/ UG trial

The ANOVA is shown in table 2

| ANOVA | | | | | | |
|----------------|---------|------|------------|---------|------|--|
| Score | Sum | of | Mean | | | |
| | Squares | df | Square | F | Sig. | |
| Between Groups | 23577.6 | 9.0 | 2619.7 | 11227.4 | 0.0 | |
| Within Groups | 4.7 | 20.0 | <u>0.2</u> | | | |
| Total | 23582.3 | 29.0 | | | | |

Table 2: One way ANOVA between groups

The residual mean square within groups was used to calculate the variation in score that will occur 95% of the time according to Bland (1995) as outlined below:

| | | |
|---|--------|---------|
| Difference between the measurements will lay with a probability of 0.95 | | |
| $0.23 \times 1.96 =$ | 0.4508 | degrees |

Table 3: Calculation according to Bland (1995)

This shows that the magnitude of error will be 0.45° throughout all readings.

It may be observed that up to 50° there is excellent agreement between the EGM and the UG. However, at higher readings, error increases. This is shown in figure 1.

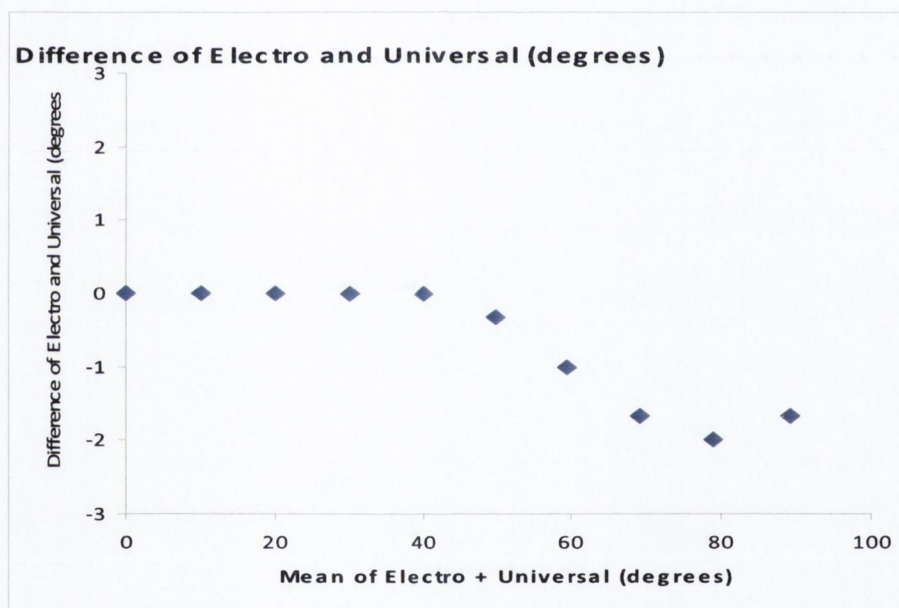


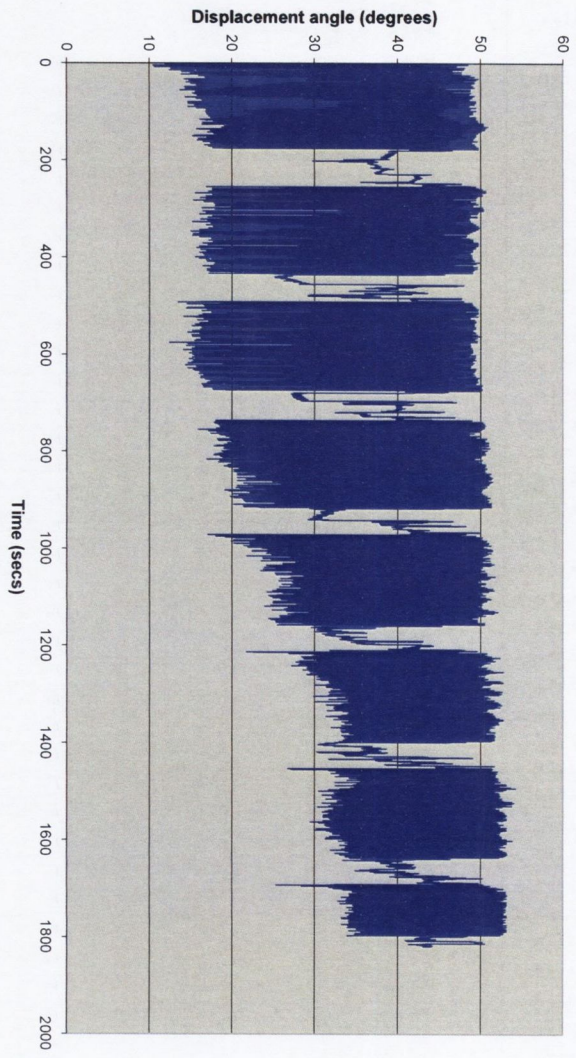
Figure1: Comparison of EGM and UG recordings.

Conclusion

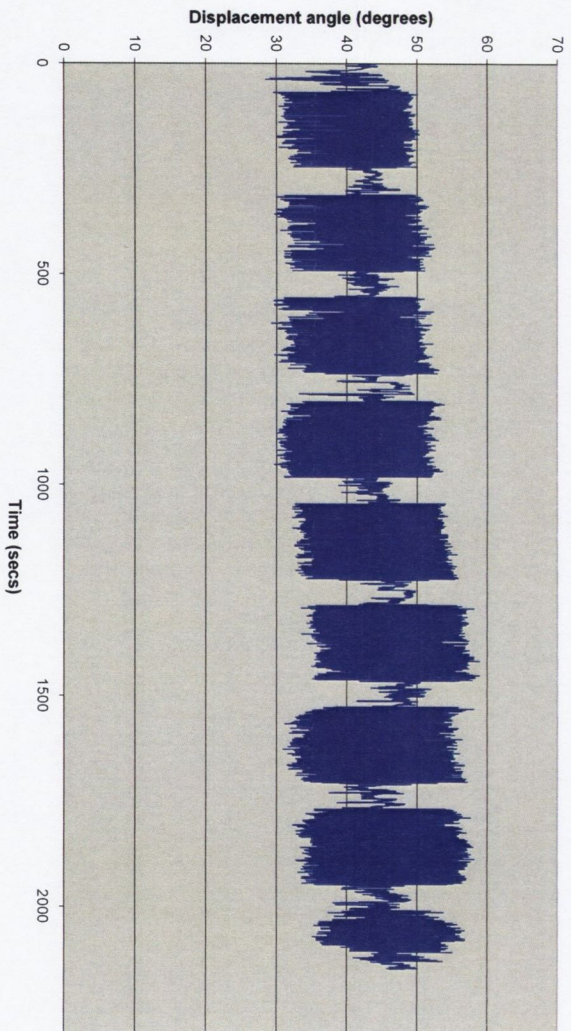
The EGM is suitable for measuring range of motion with an inherent error of 0.45° .

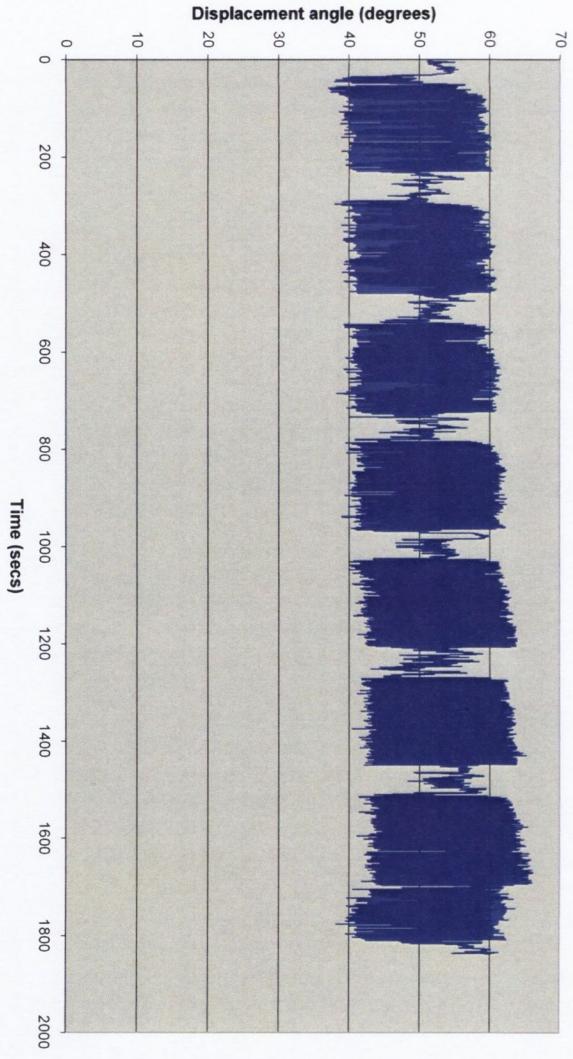
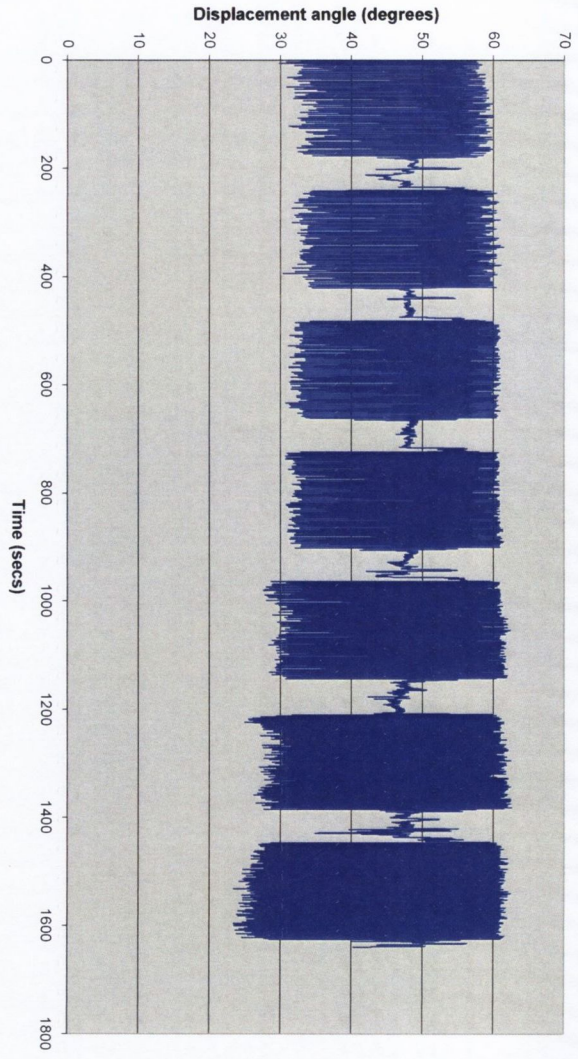
*APPENDIX I,
ERGOMETER AND BOAT GRAPHS, STUDY 5.*

Subject 1 : Ergometer step test

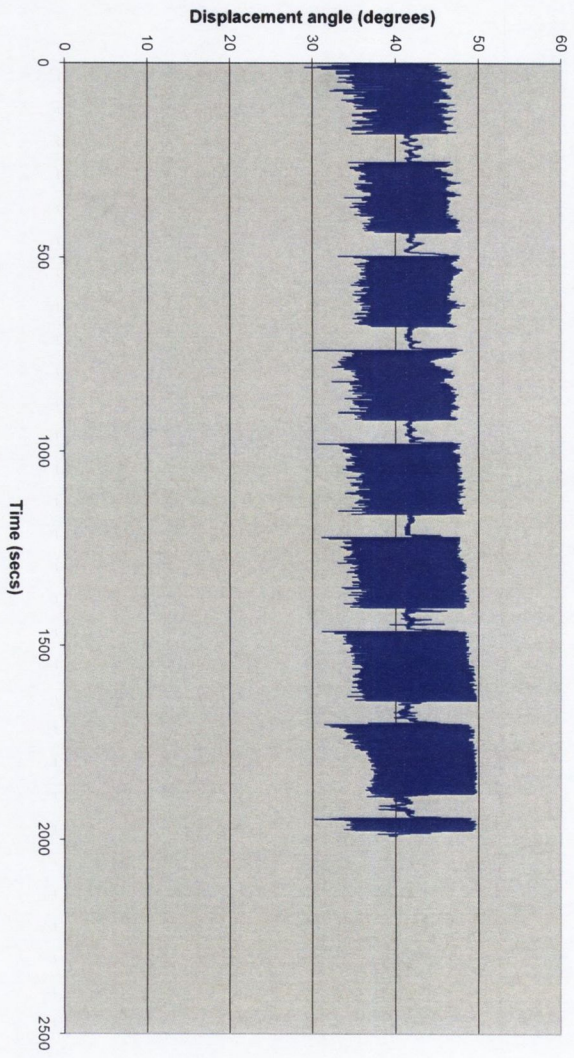


Subject 1 : Boat step test

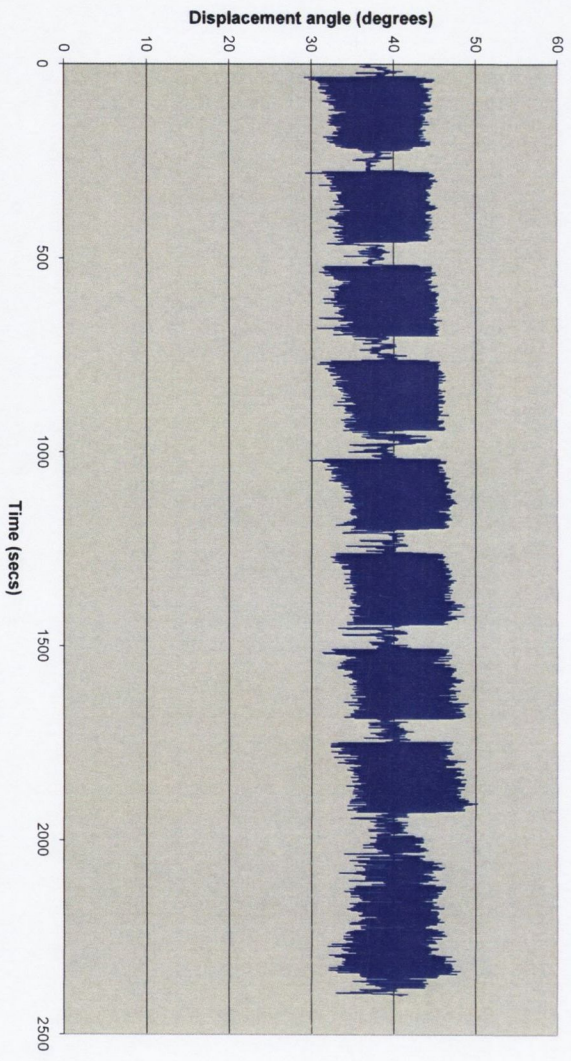


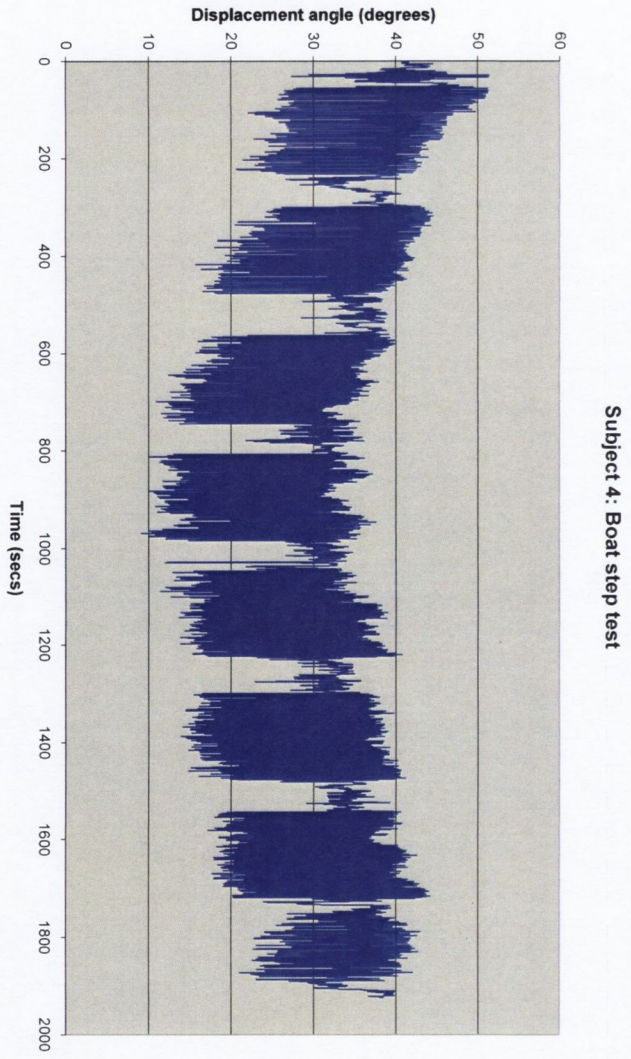
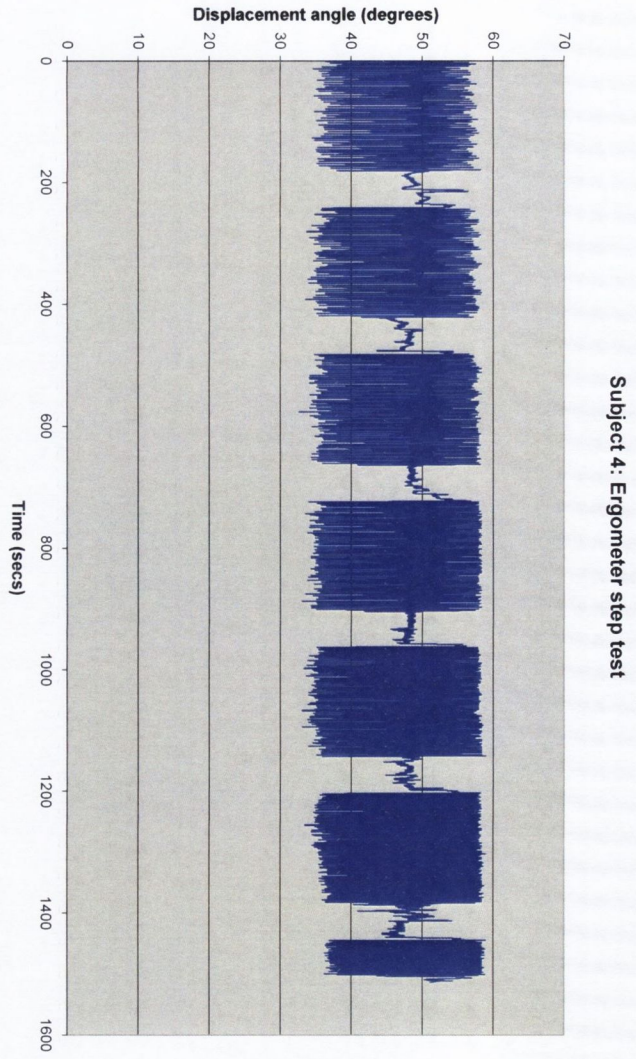


Subject 3: Ergometer step test

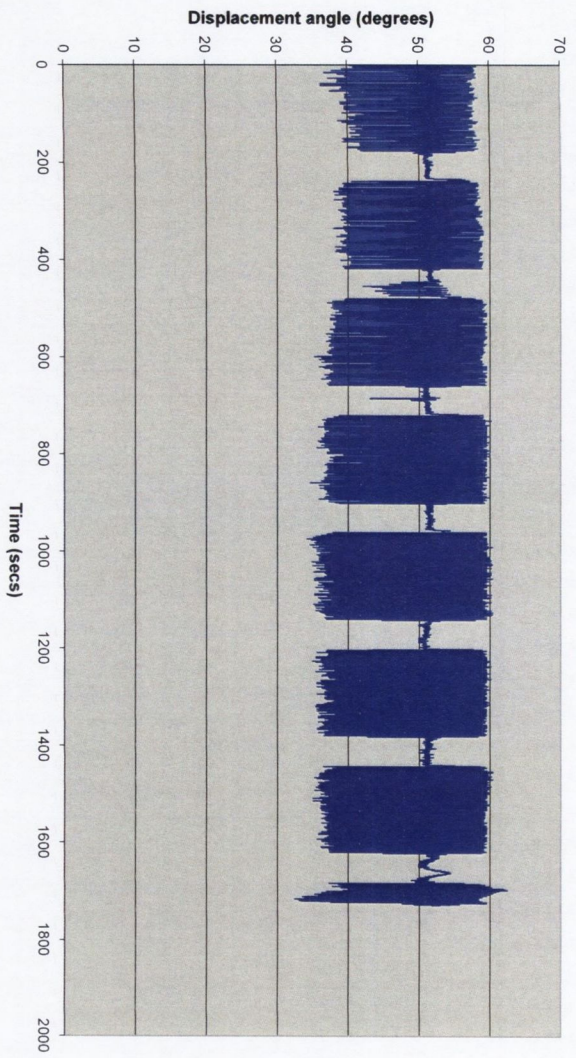


Subject 3: Boat step test

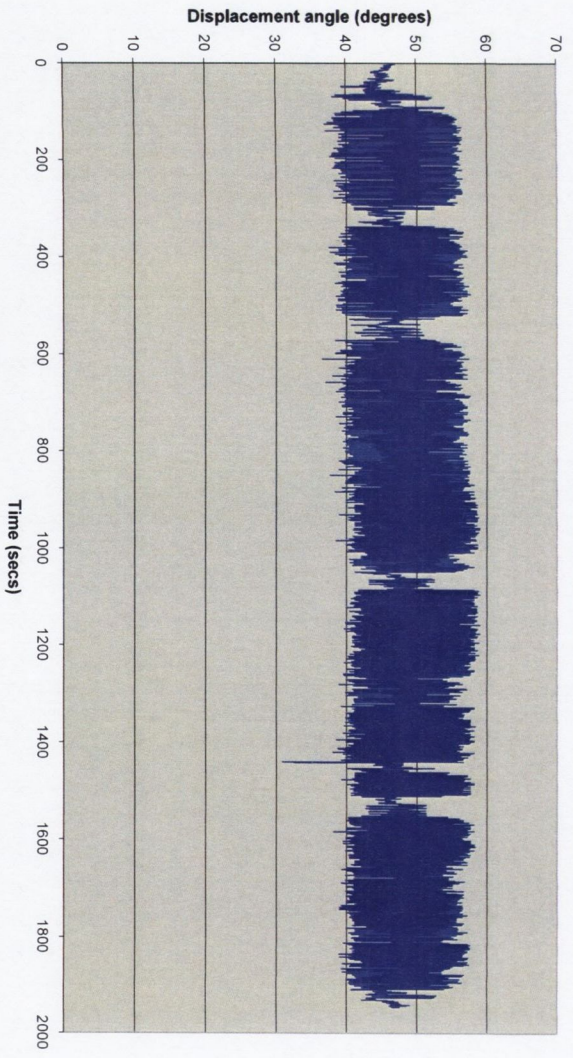


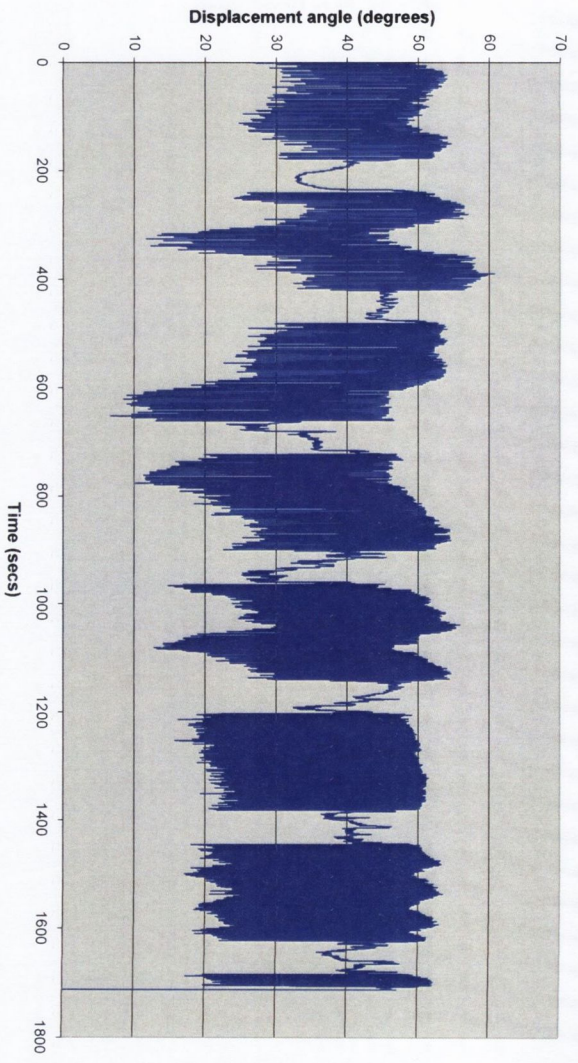


Subject 5: Ergometer step test

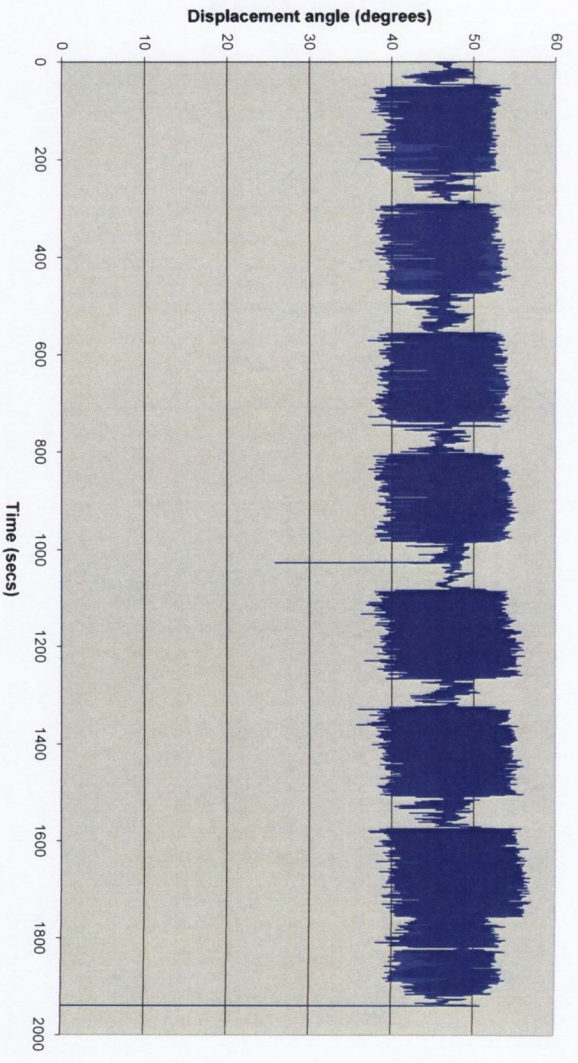


Subject 5: Boat step test

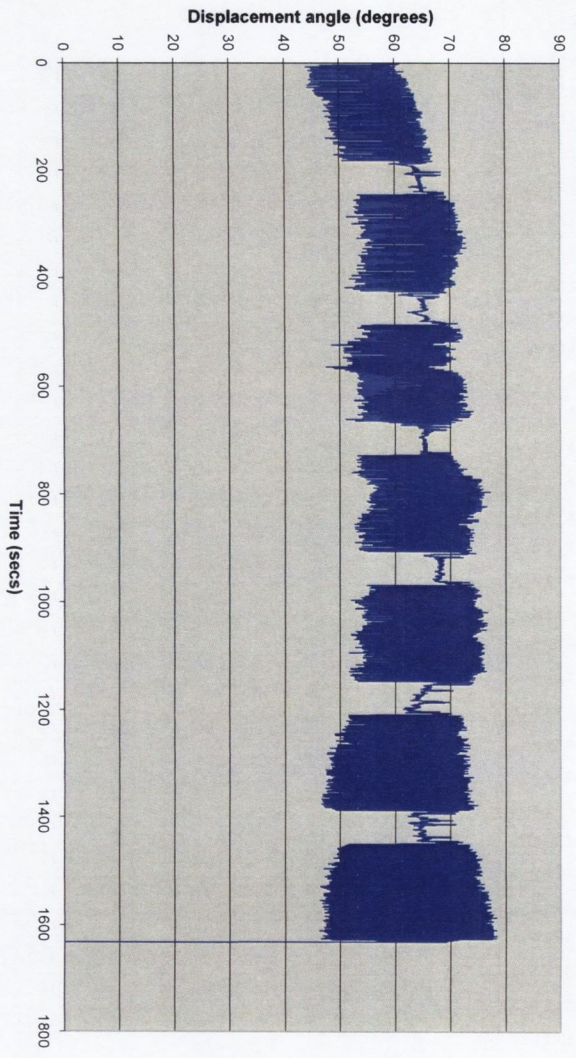




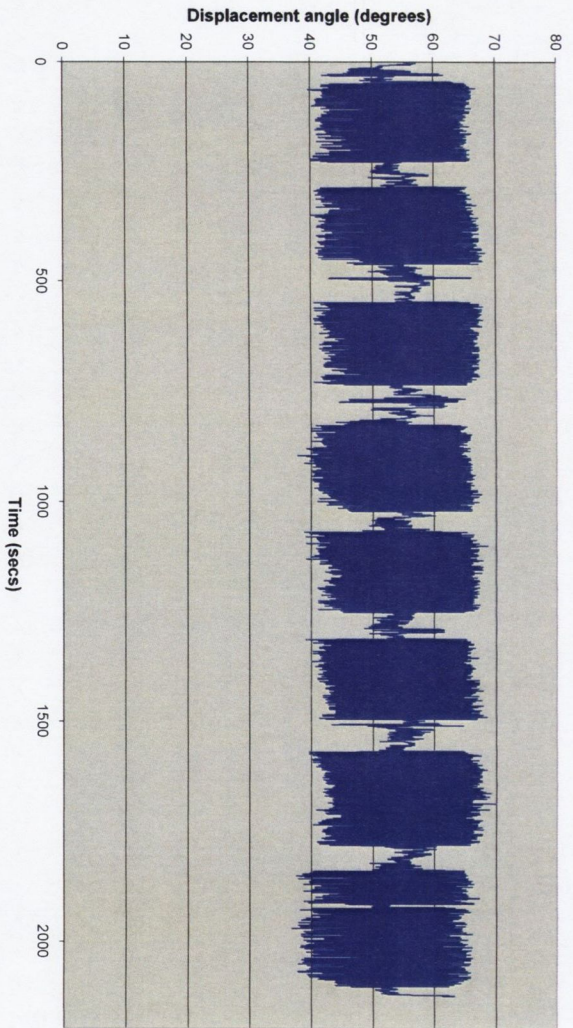
Subject 6: Ergometer step test



Subject 6: Boat step test

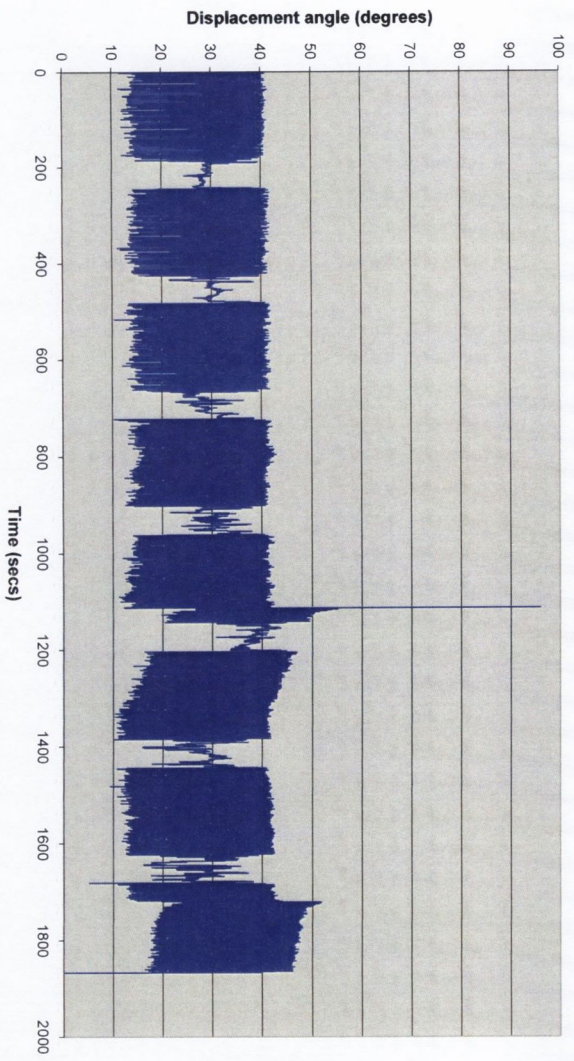


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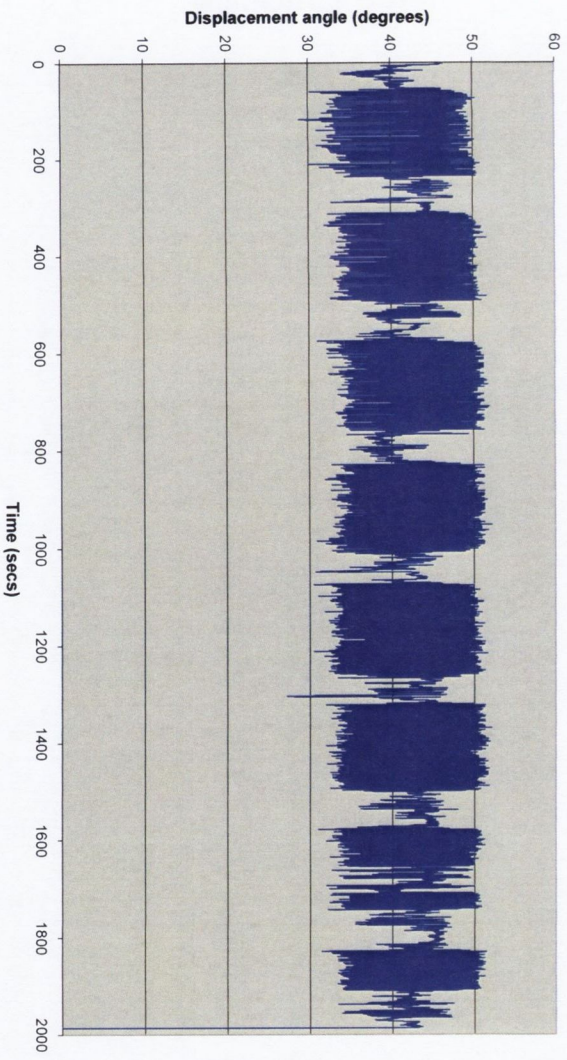


Subject 7: Boat step test

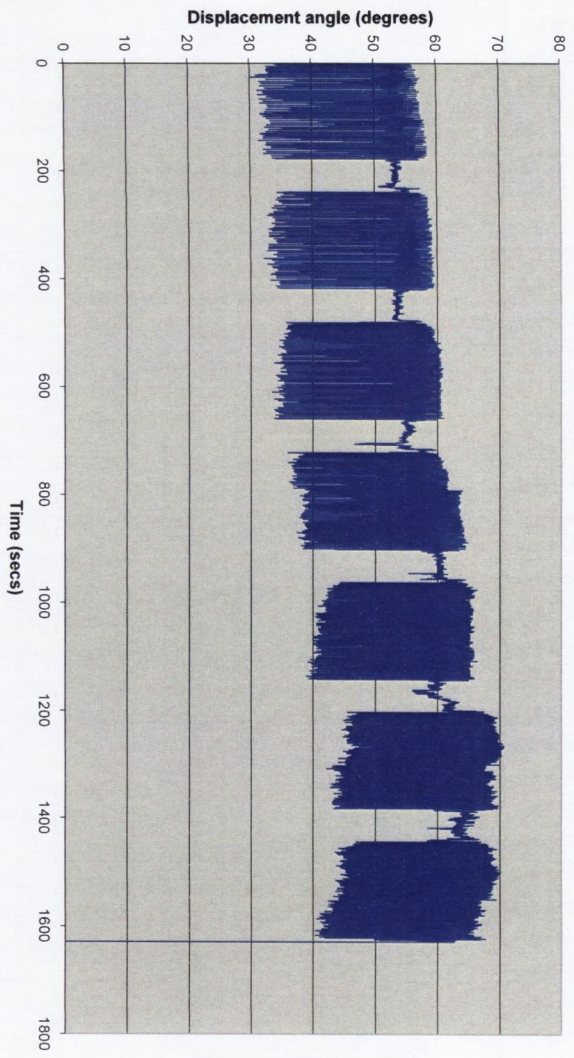
Subject 8: Ergometer step test



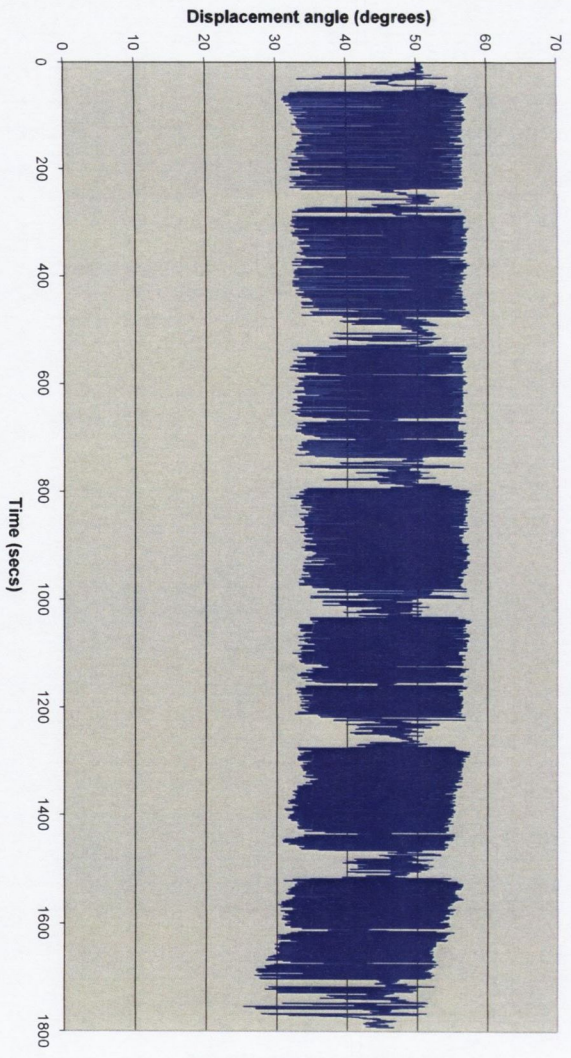
Subject 8: Boat step test

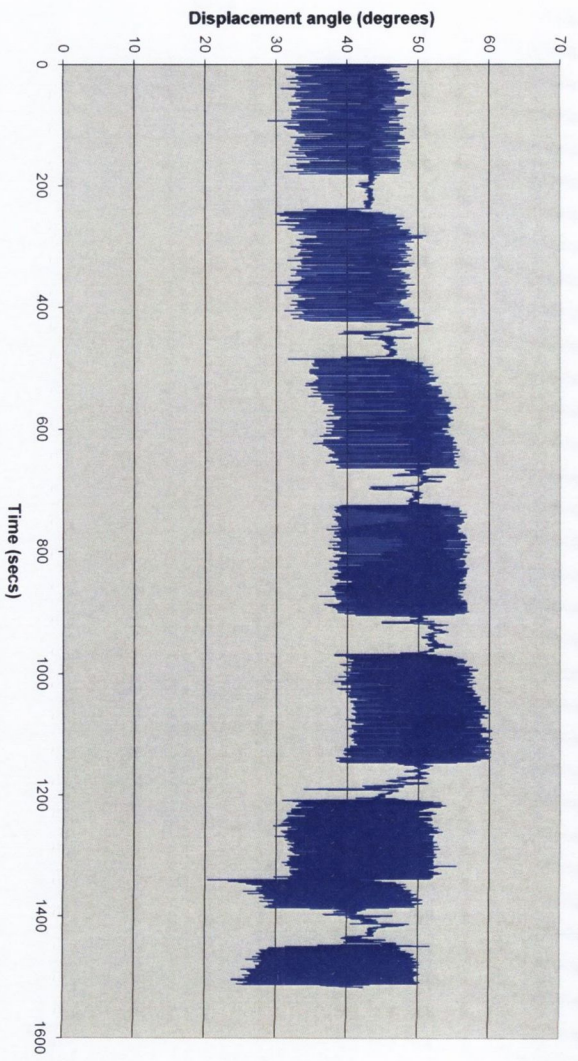


Subject 9: Ergometer step test

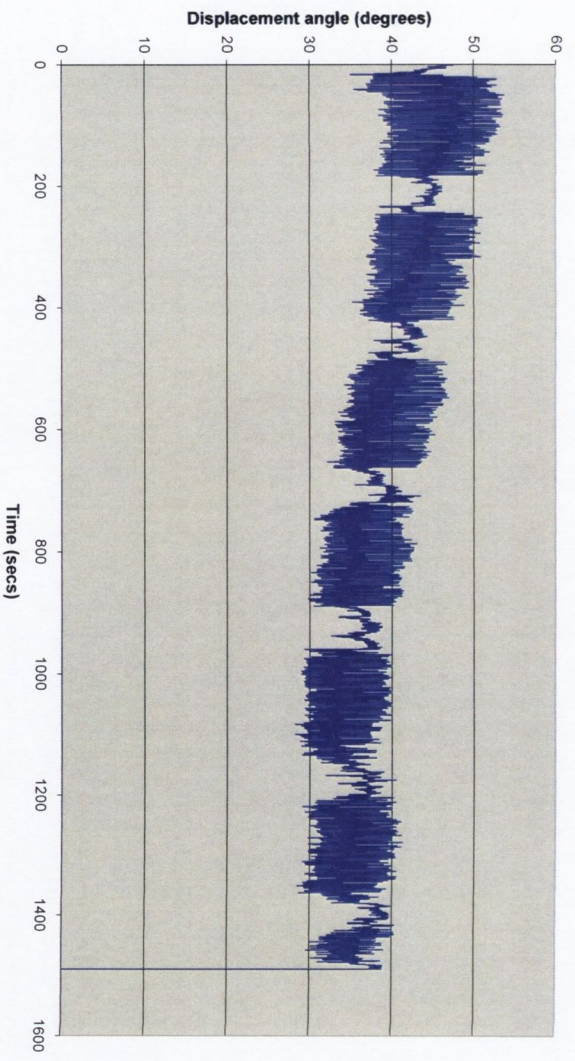


Subject 9: Boat step test

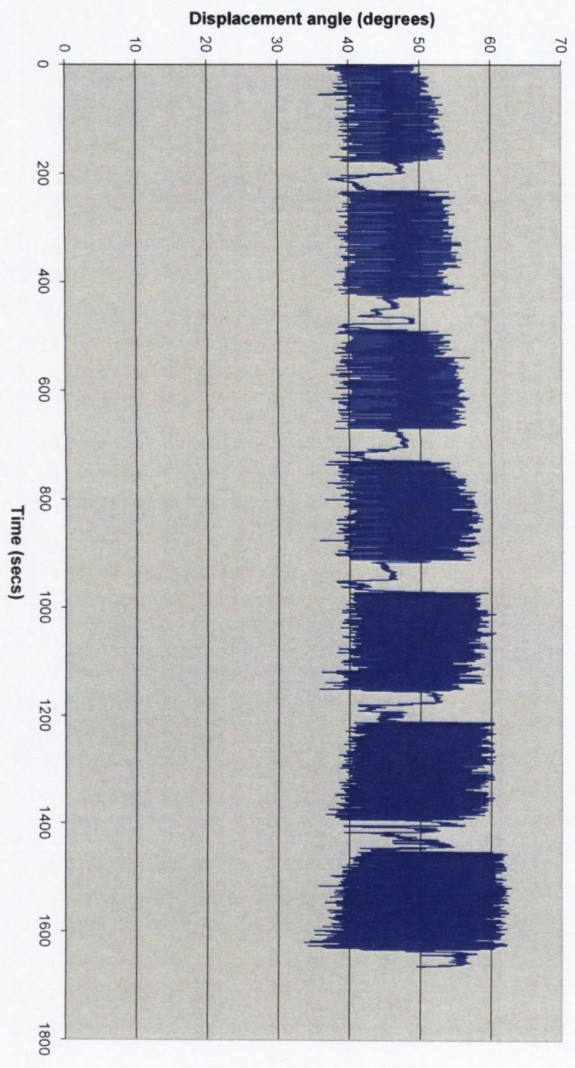




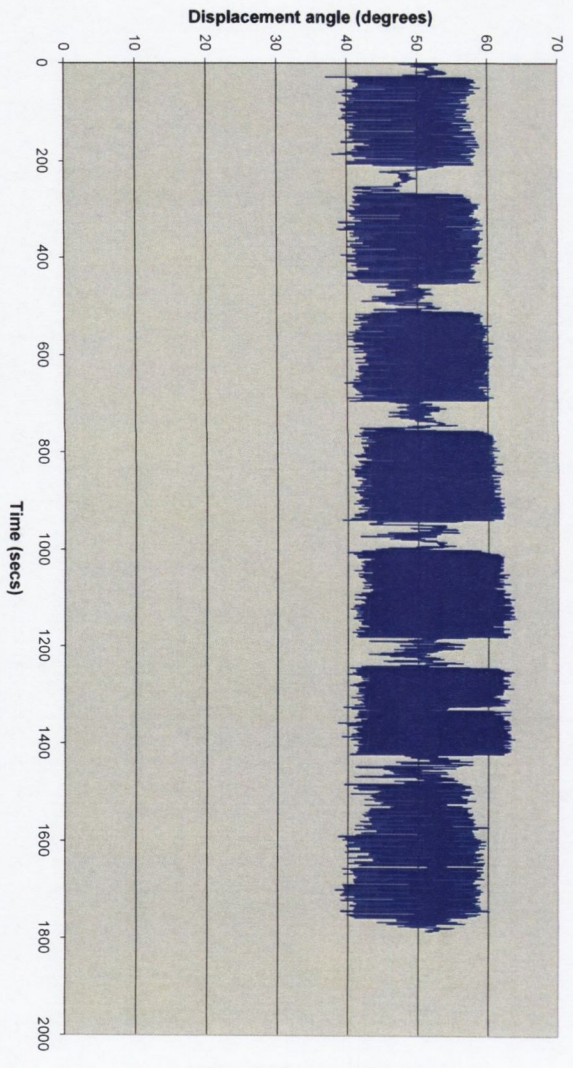
Subject 10: Boat step test



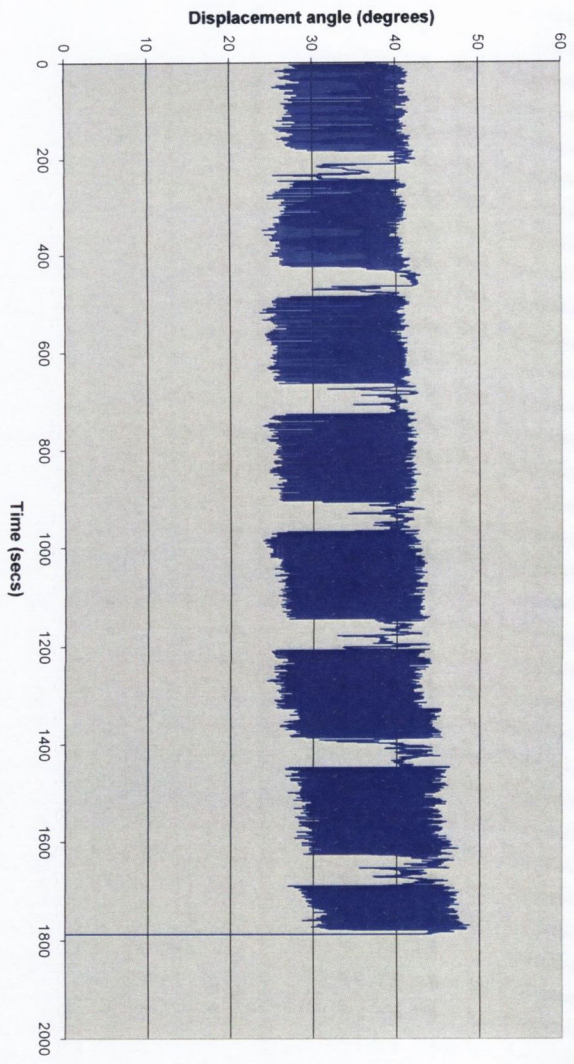
Subject 11 : Ergometer step test



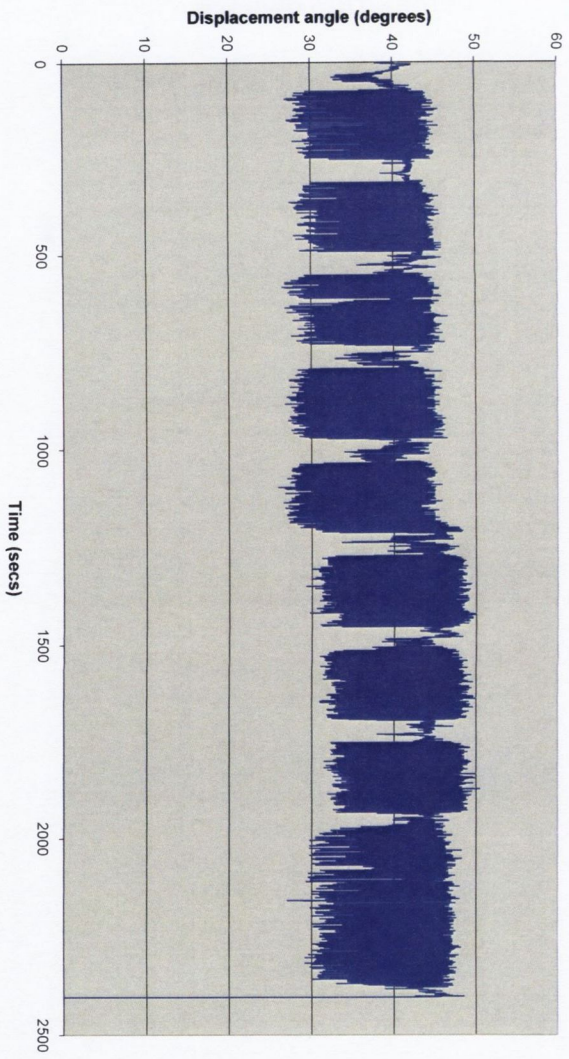
Subject 11 : Boat step test

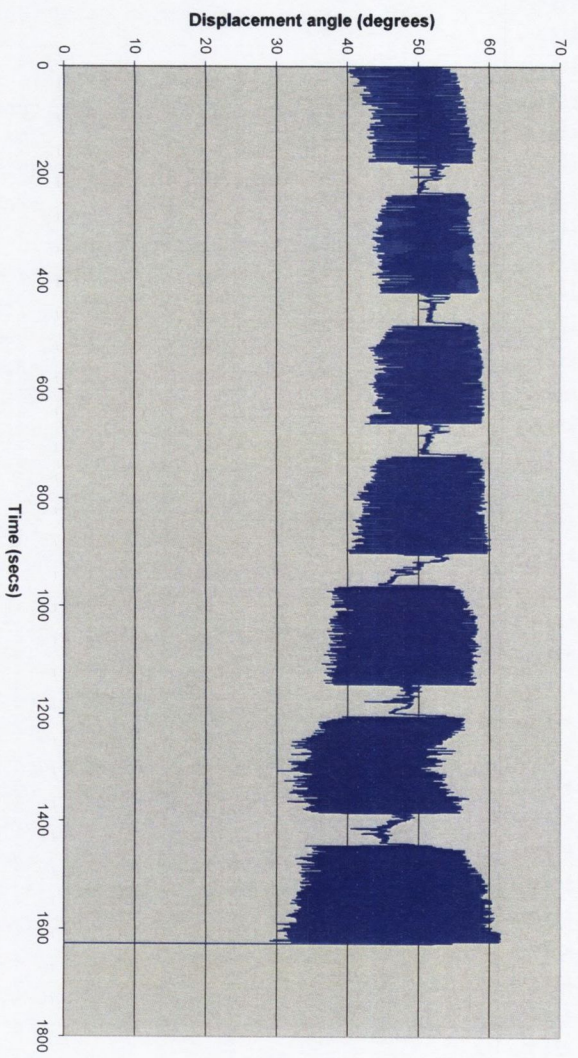


Subject 12: Ergometer step test

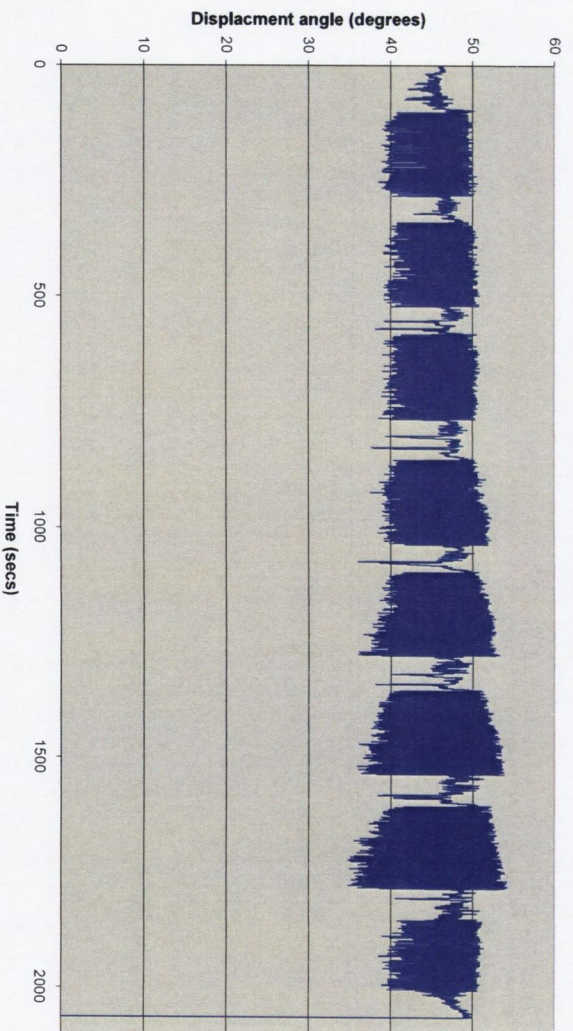


Subject 12: Boat step test



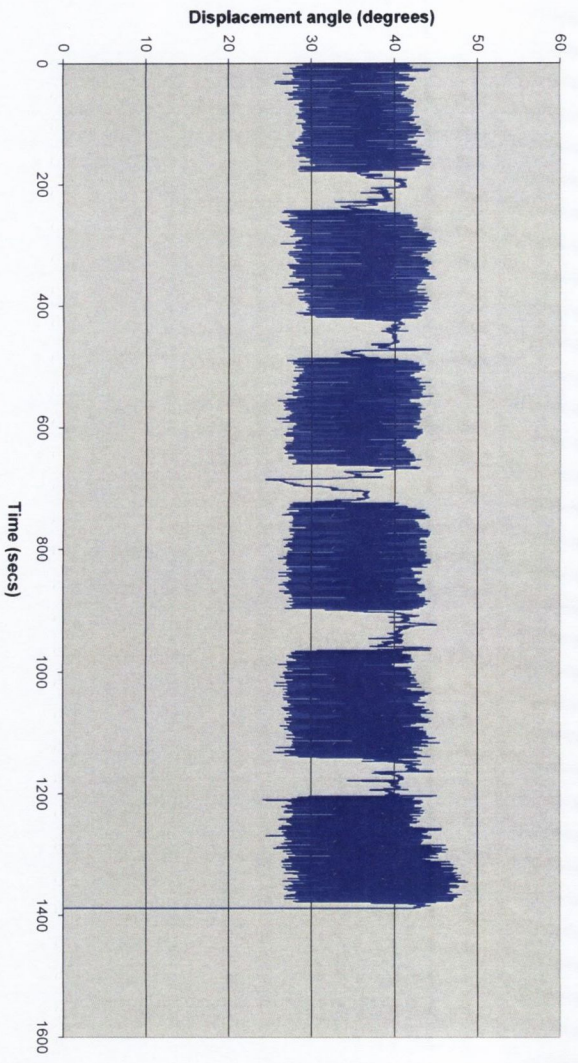


Subject 13: Ergometer step test

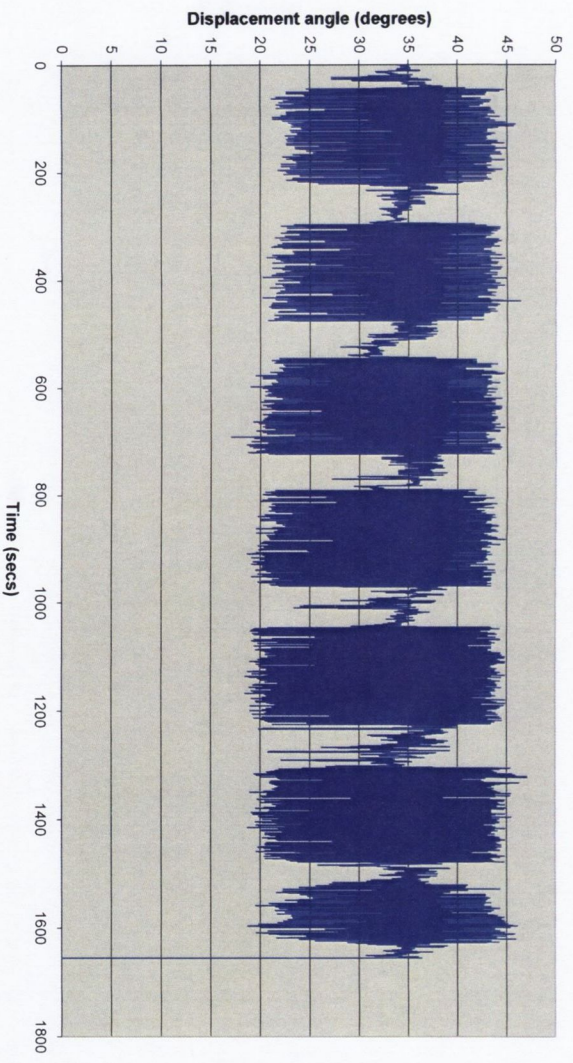


Subject 13: Boat step test

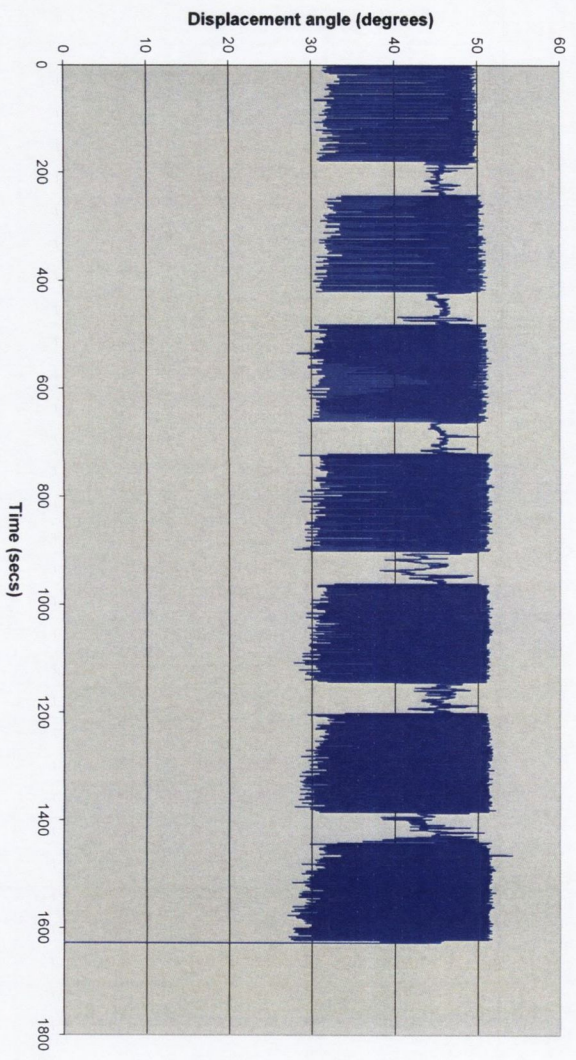
Subject 14: Ergometer step test



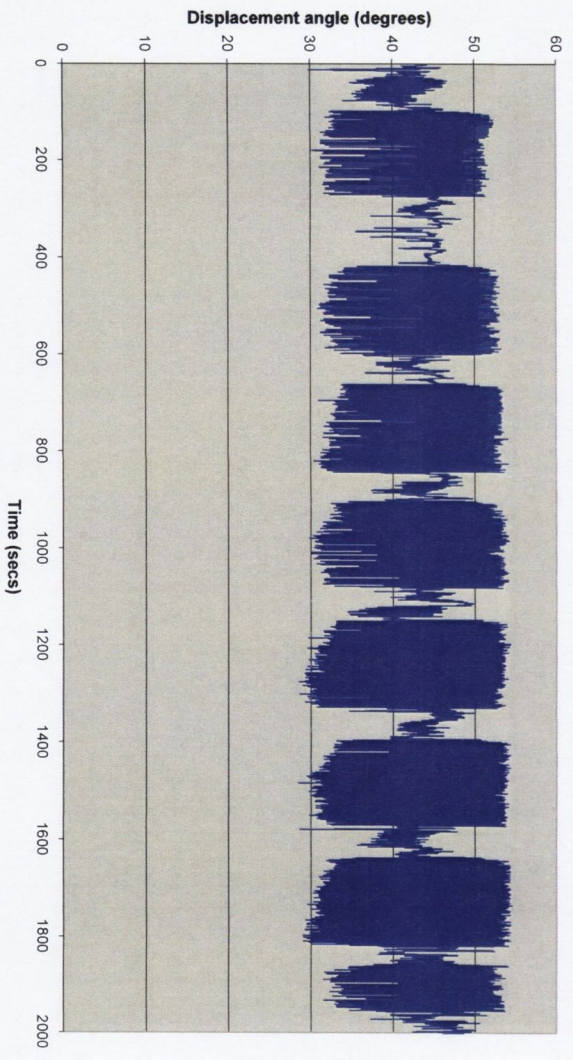
Subject 14: Boat step test

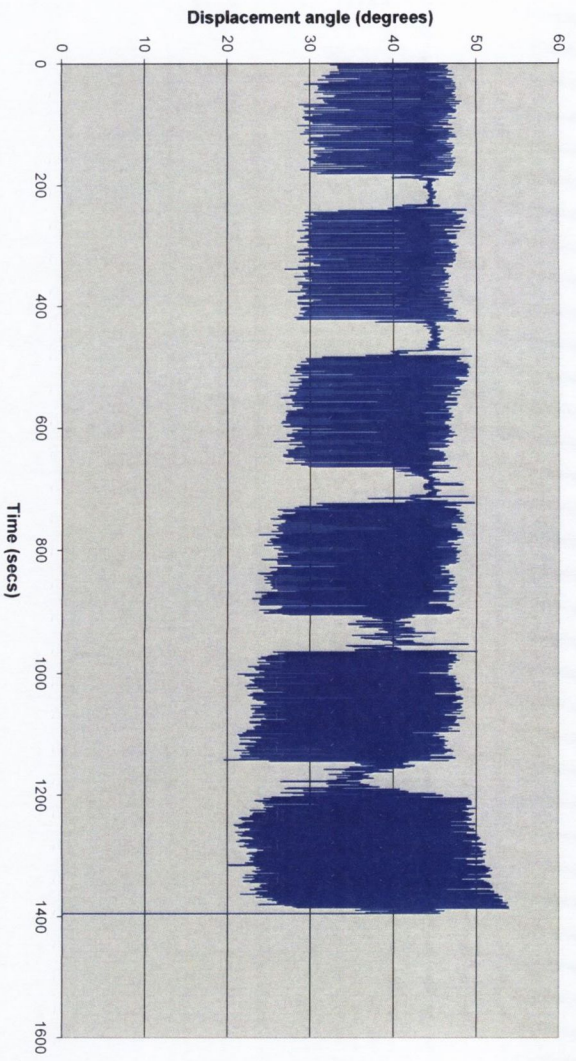


Subject 15: Ergometer step test

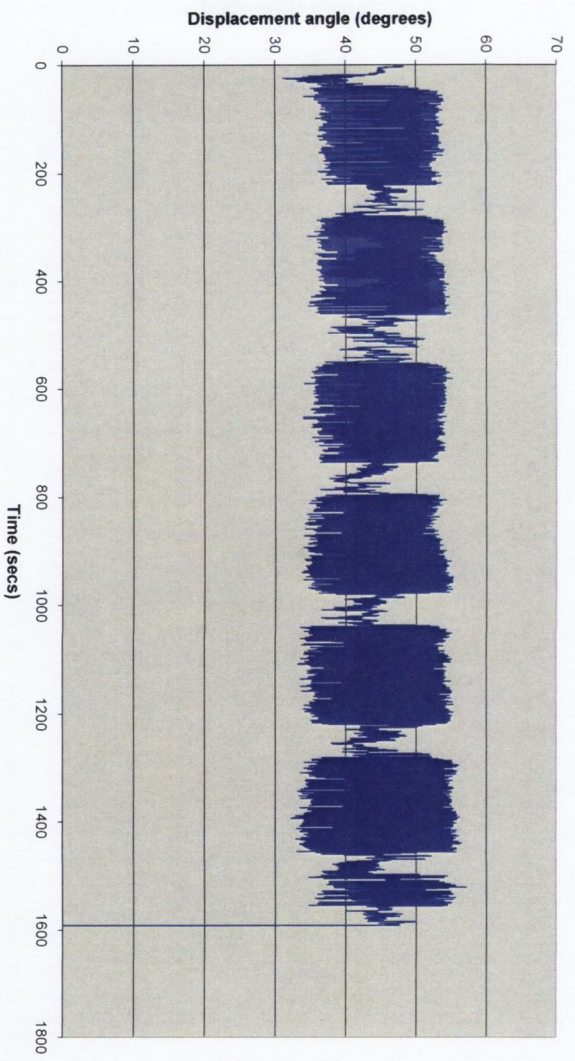


Subject 15: Boat step test



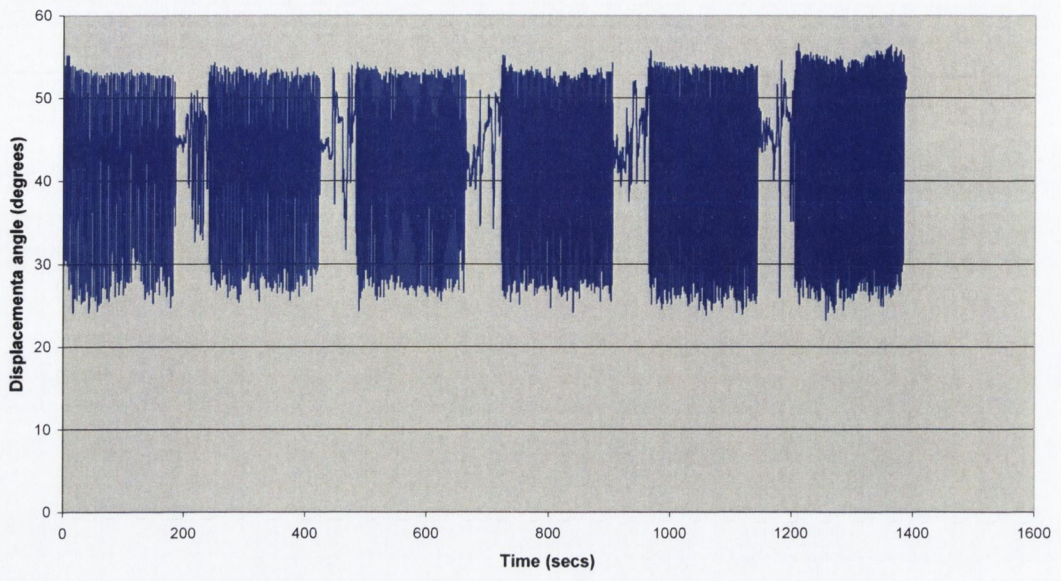


Subject 16: Ergometer step test

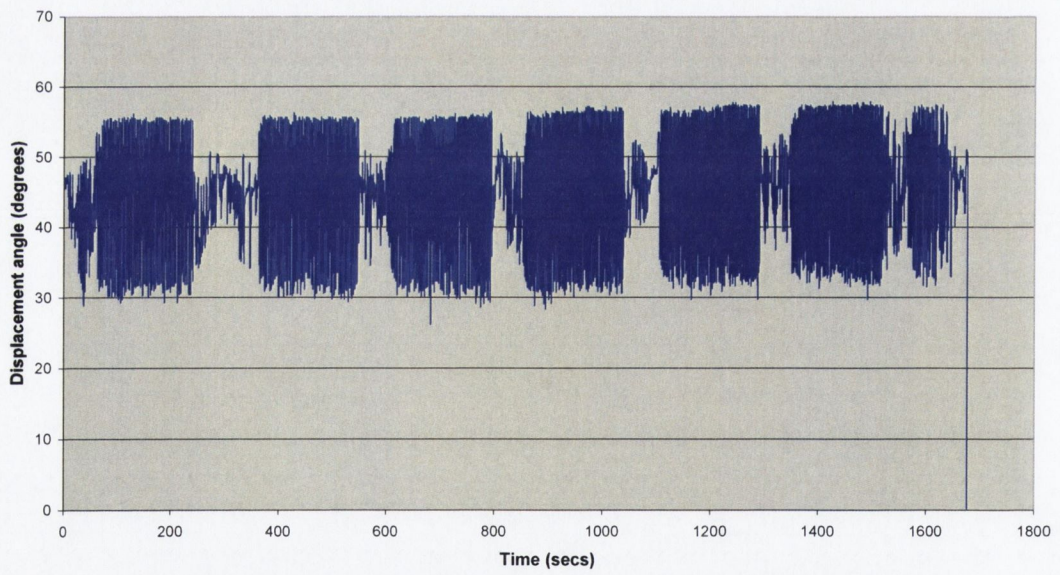


Subject 16: Boat step test

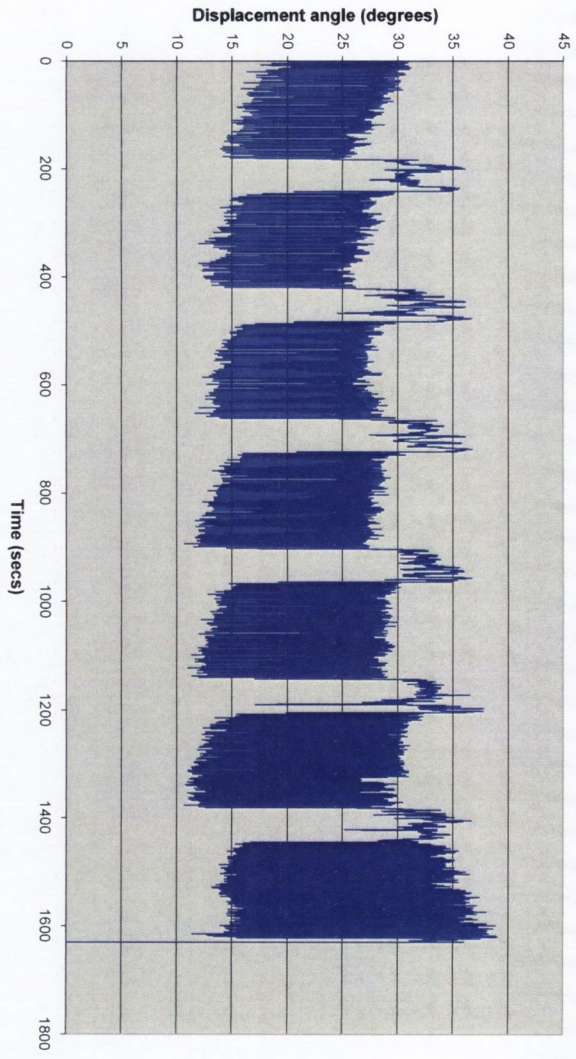
Subject 17: Ergometer step test



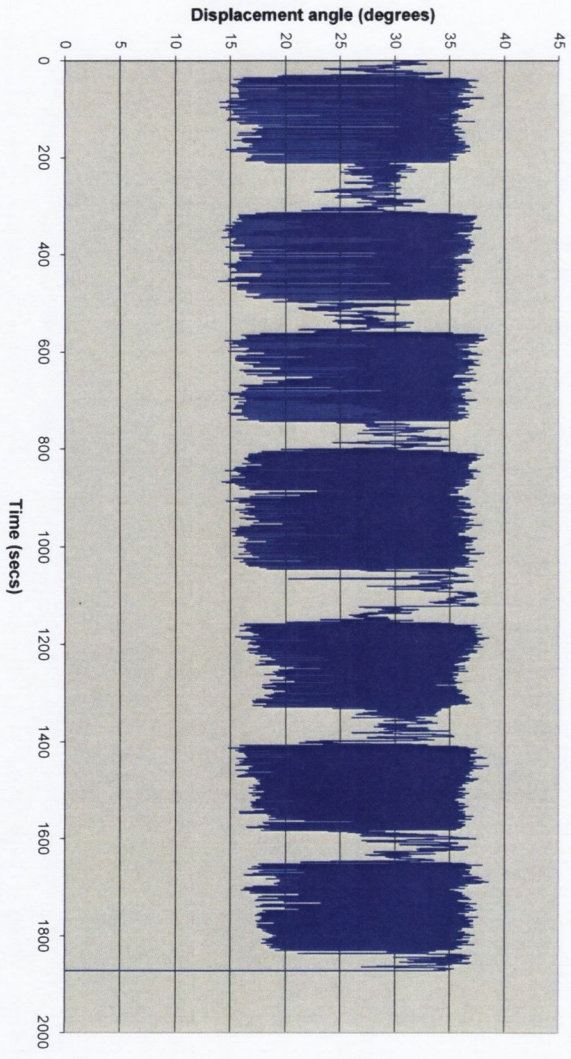
Subject 17: Boat step test



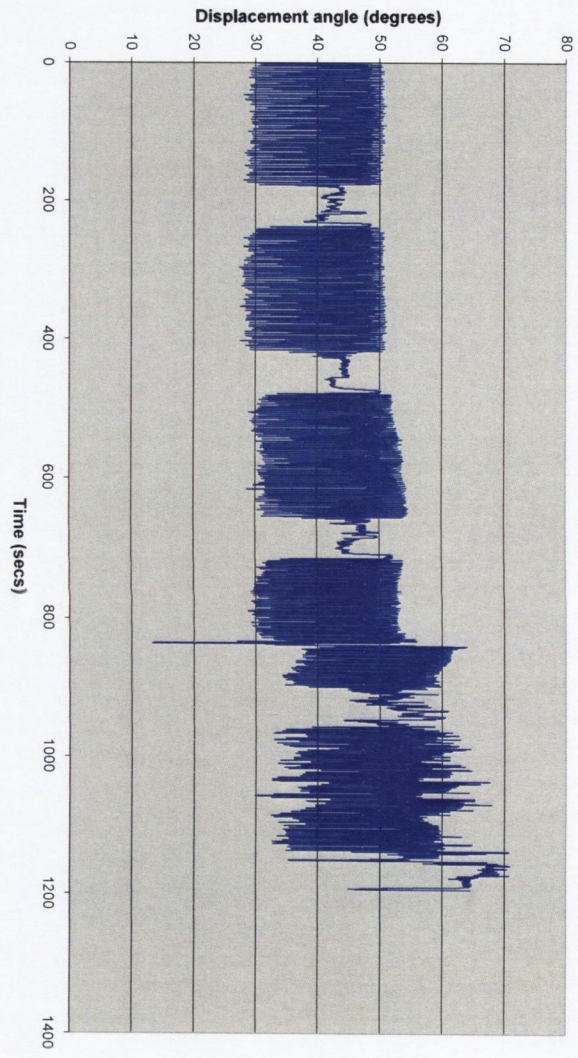
Subject 18: Ergometer step test



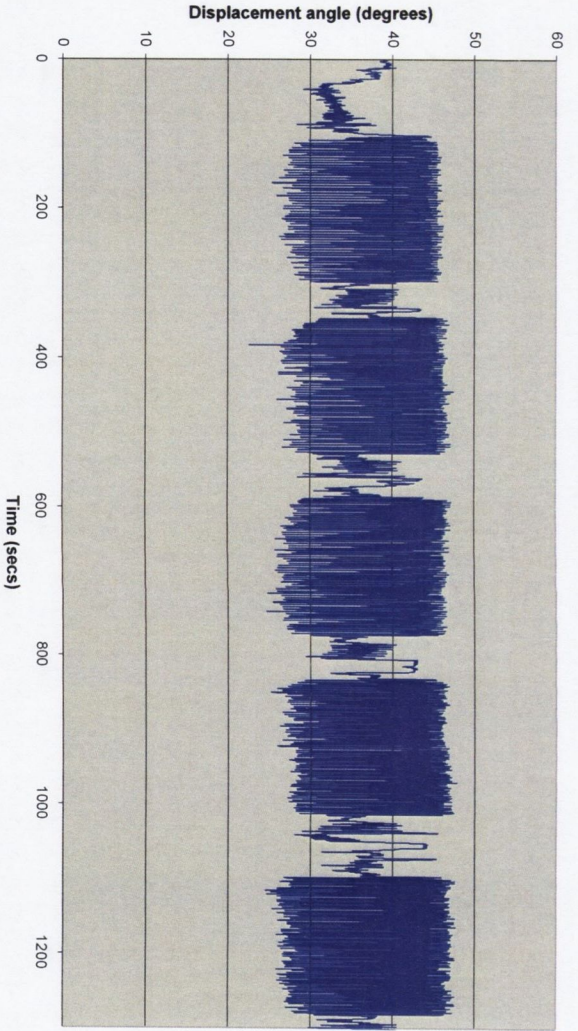
Subject 18: Boat step test



Subject 19: Ergometer step test



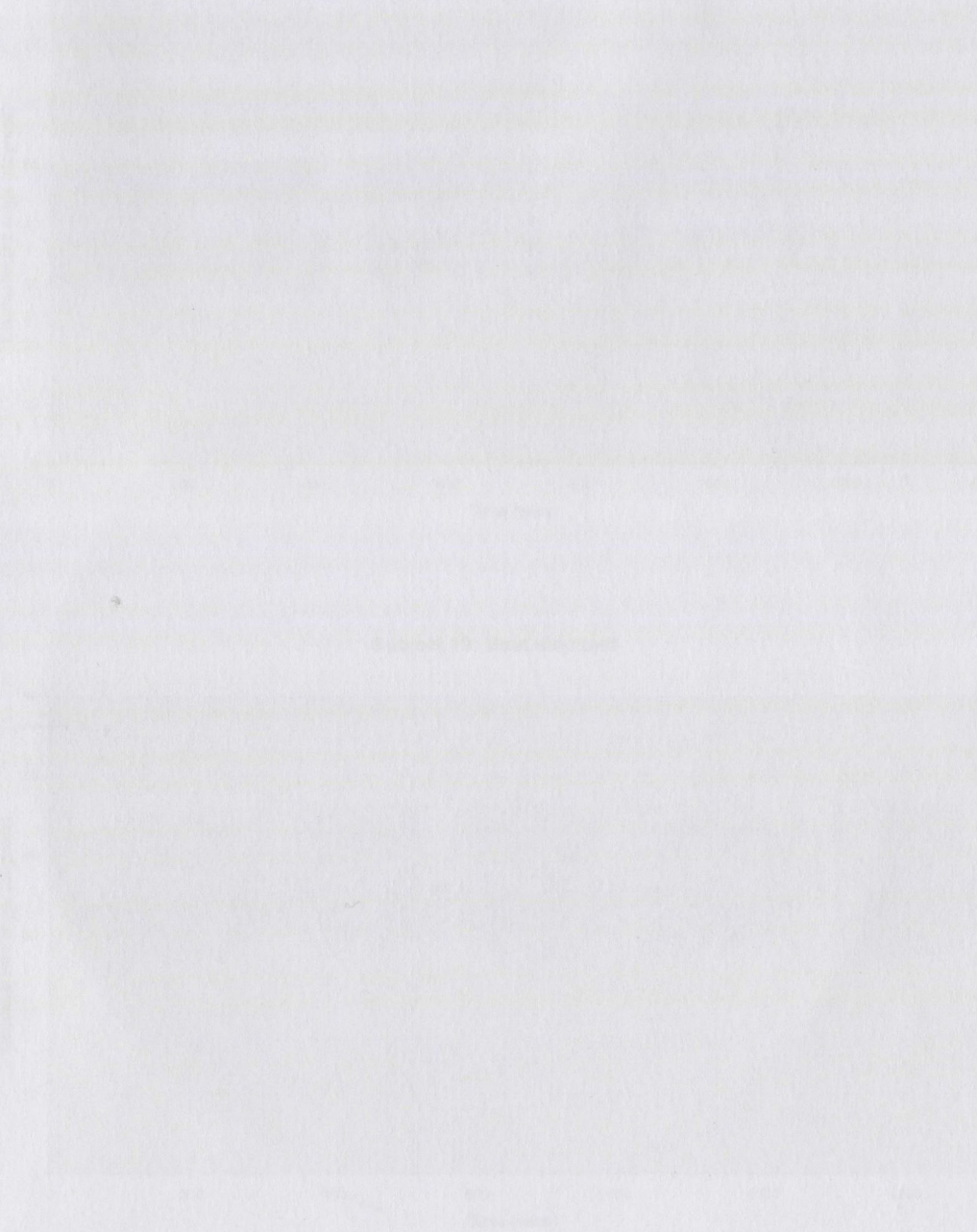
Subject 19: Boat step test



APPENDIX J

PUBLISHED WORK FROM THIS THESIS.

RESEARCH ON THE STATE



APPENDIX K
RAW DATA





A 12-month prospective cohort study of injury in international rowers

F Wilson, C Gissane, J Gormley, et al.

Br J Sports Med 2010 44: 207-214 originally published online August 21, 2008

doi: 10.1136/bjasm.2008.048561

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A 12-month prospective cohort study of injury in international rowers

F Wilson,¹ C Gissane,² J Gormley,¹ C Simms³

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