PREDICTING ROWING KINEMATICS AND KINETICS BASED ON ERGOMETER INSTRUMENTATION ALONE

by

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Declaration of Originality

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Abstract
The aims of this thesis were to identify opportunities to improve the measurement of ergometer rowing through instrumentation of the ergometer, and investigate if such measurements had a potential to predict other variables. It was hypothesised that measurements describing rowing technique, measured in three-dimensional space, could be predicted from those that can be measured using less complex methods. The kinematic measurements that describe rowing technique normally require complicated and expensive systems featuring motion tracking and force measurements. Establishing any relationships would allow for assessment of an athlete’s technique to be made with less complex equipment, allowing more individuals to assess quality of their movement with respect to the performance predictors suggested in the rowing research literature.

A novel opportunity to measure kinematics of the rowing ergometer was found, and consequently a device to measure the motion of the ergometer seat was designed and integrated into a kinematic and kinetic measurement system.

14 elite athletes completed a protocol of increasing intensity. For the first time, the motion of the ergometer seat was measured simultaneously with full three-dimensional kinematics and kinetics of the rowing activity. The key finding of this study was that a combination of measurements on the instrumented ergometer could predict to an accuracy of 2° and 60mm, kinematic and kinetic measures that normally require instrumentation of the athlete, and have been shown to be predictors of performance.

The results of this work indicate that predictions of kinematic measurements during ergometer rowing that would normally require direct measurement with complicated and sensitive equipment can be made using ergometer instrumentation alone. Thus measurements that are relatively simple to acquire compared to 3D kinematics and motion capture equipment, via instrumentation of a rowing ergometer or even of a rowing boat on water could be used as a biofeedback tool to improve quality of movement of the rowing population. Flexion and extension of the lumbar spine, translation of the lumbar spine and predictions of discrete timing points of the rowing stroke can be anticipated using such a system. While the exact predictive relationships developed are subject to the limitations of
the study, the predictive capacity of the relationship between 3D kinematic variables and those measured using an instrumented ergometer has been demonstrated. These relationships provide vastly more information that would otherwise be available to those without human motion capture equipment, and thus this work has signposted future research and a potential to improve the technique, performance and enjoyment of the sport of rowing.

The consequence of this work is that the biofeedback systems, and understanding of the rowing stroke developed by rowing biomechanists in past literature may be made more accessible and utilised by a wider population of rowers. An instrumented ergometer and the developed relationships can quantify aspects of rowing coaching, increasing the accessibility to assessing rowing technique, identify opportunities for improvement, suggestions of methods to make such improvements and continuously assessing the effectiveness of this process and informing longitudinal maintenance of these improvements.
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Glossary and Nomenclature

<table>
<thead>
<tr>
<th>Class/group</th>
<th>Category of athlete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footstretcher/plate</td>
<td>Plate upon which the feet are constrained and press against on an ergometer or rowing boat</td>
</tr>
<tr>
<td>Handle</td>
<td>Equipment the athlete holds to apply power to oar (on-water) or ergometer</td>
</tr>
<tr>
<td>Seat</td>
<td>Equipment upon which the athlete sits</td>
</tr>
<tr>
<td>Slide</td>
<td>Equipment upon which the seat is constrained to move in an anterior-posterior direction</td>
</tr>
<tr>
<td>Step</td>
<td>A piece of rowing activity. Steps are incremental pieces of activity.</td>
</tr>
<tr>
<td>Stroke</td>
<td>One complete cycle of rowing motion</td>
</tr>
<tr>
<td>Catch</td>
<td>The start, most anterior position of the rowing stroke</td>
</tr>
<tr>
<td>Drive</td>
<td>The section of the stroke propulsive force is applied</td>
</tr>
<tr>
<td>Finish</td>
<td>The end of the drive phase of the rowing stroke</td>
</tr>
<tr>
<td>Knees up</td>
<td>Onset of knee joint flexion on recover</td>
</tr>
<tr>
<td>MHF</td>
<td>Maximum handle force</td>
</tr>
<tr>
<td>Rate, stroke rate</td>
<td>Number of cycles of rowing strokes performed per minute</td>
</tr>
<tr>
<td>Recovery</td>
<td>The phase where the athlete moves from finish to catch</td>
</tr>
<tr>
<td>Rockover</td>
<td>Description of the anterior rotation of the pelvis during the recover</td>
</tr>
<tr>
<td>%</td>
<td>In context with the above represents the timing of this point</td>
</tr>
</tbody>
</table>

2D                  | Two dimensions/dimensional                                                             |
3D                  | Three dimensions/dimensional                                                           |
AJC                 | Ankle Joint Centre                                                                     |
AP                  | Anterior-posterior                                                                      |
BM                  | Body Mass                                                                               |
BW                  | Body Weight                                                                             |
CMD                 | Coefficient of Multiple Determination                                                    |
COP                 | Centre of Pressure on ergometer seat                                                    |
CTF                 | Timing difference between the onset of posterior travel of the seat and handle          |
CV                  | Coefficient of Variance                                                                 |
Femur               | Body segment - thigh                                                                   |
FOB                 | Flock of Birds motion tracking hardware                                                 |
HJC                 | Hip Joint Centre                                                                        |
HWM                 | Athlete group/class – open-weight male                                                  |
HWW                 | Athlete group/class – open-weight female                                                |
IES                 | Instrumented Ergometer System                                                           |
Inflection          | Change of direction of motion                                                           |
IS                  | Superior-inferior                                                                       |
KJC                 | Knee Joint Centre                                                                       |
L5/S1, LSJ          | Junction of fifth lumbar and first sacral vertebrae                                     |
LTR                 | Leg to Trunk Ratio                                                                      |
LP                  | Left foot plate                                                                         |
LWM                 | Athlete group/class – lightweight male                                                  |
LWW                 | Athlete group/class – lightweight female                                                |
MHF                 | Maximum Handle Force                                                                    |
ML                  | Medio-lateral                                                                           |
RP                  | Right foot plate                                                                        |
S1                  | Flock of Birds sensor 1                                                                  |
S2                  | Flock of Birds sensor 2                                                                  |
S3                  | Flock of Birds sensor 3                                                                  |
S4                  | Flock of Birds sensor 4                                                                  |
SI1                 | Seat Inflection 1                                                                        |
SI2                 | Seat Inflection 2                                                                        |
SIF                 | Seat Inflection Front                                                                   |
Tibia               | Body segment - shank                                                                     |
VIF                 | Variation Influence Factor                                                               |
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>Laboratory medio-lateral axis</td>
</tr>
<tr>
<td>Y</td>
<td>Laboratory vertical axis</td>
</tr>
<tr>
<td>Z</td>
<td>Laboratory anterior-posterior axis</td>
</tr>
<tr>
<td>α</td>
<td>Intersegmental angle of flexion-extension</td>
</tr>
<tr>
<td>β</td>
<td>Intersegmental angle of abduction-adduction (side flexion)</td>
</tr>
<tr>
<td>γ</td>
<td>Intersegmental angle of internal-external rotation (twist)</td>
</tr>
<tr>
<td>ΔLSJ catch – MHF</td>
<td>Change LSJ flexion during drive phase from catch to MHF</td>
</tr>
</tbody>
</table>
Chapter 1  Introduction

1.1 Background

The act of propelling a boat by moving oars through the water, with the oars fixed to a point on the vessel has origins in early human history. Rowing has been used for transportation, pleasure and competition. In modern competitive rowing the goal is to race a fixed distance in as short a time as possible. Race types and distances vary, however, athletes generally focus upon the format used in the pinnacle of the sport, the Olympics - these are 2000 metre courses, divided into 6 or more equal lanes for multiple boats to race simultaneously from start to finish.

Competitive rowing on water is segmented into different classifications depending on rowing category, boat size, gender and weight class. There are two categories of rowing, sweep and sculling. Sweep rowing is where each crew member uses a single oar, fixed to an outboard pivot mounted on a boat on either their left or right, and in an asymmetric movement, rotate their torso as the oar covers its arc of travel. Sweep crews consist of 2, 4 or 8 athletes. The other category is sculling, where each athlete uses two oars, one in each hand, in a symmetrical movement in boats for 1, 2 or 4 individuals. Athletes are classified as open weight or lightweight, with the maximum limit for the latter being 72 kg and 59 kg for men and women respectively.

A distance of 2000 m requires both power and endurance to bring a combined boat and crew weighing up to 1000 kg to racing speed and then sustain to complete the race distance. Two kilometre racing uses approximately 25 % anaerobic energy and 75 % aerobic, and training for rowing reflects this, utilising a wide range of training intensities (Nolte, 2011). Some training will occur above race intensity for short repeated intervals at 30 + strokes per minute, but the majority being undertaken at low intensity for 60 - 90 minutes at a lower rate of 18 - 20 strokes per minute (Nolte, 2011).

Further to aerobic and anaerobic capacity, athlete morphology and technical efficiency are the principal variables between competitors with effective rowing requiring sufficient flexibility, core strength and muscle co-ordination (Thompson, 2005).
The act of rowing is to repeat a cyclical closed chain movement, which for elites can occur up to 1800 times in a low intensity training session, or around 250 times in a race. The stroke cycle is shown in Figure 1-1, and the catch position is shown in more detail in Figure 1-2, where knees and hips are in maximum flexion.

**Figure 1-1: Diagrams of the rowing stroke cycle**

The two distinct phases of the rowing stroke are the drive that starts at this catch position, and the recovery where the athlete returns to the catch position from the finish position. From the catch position the athlete pushes with the legs against the foot stretcher, upon which their
shoes are fixed and extends the knee and hip joint. The seat upon which the athlete sits is mounted on slides and is free to move with the athlete. The trunk and shoulder musculature activate in this process, transferring force through the arms to the handle. The majority of power is generated by the large muscle groups in the legs and hips, and so it is important that the trunk acts as a link in a kinetic chain, generating and transferring forces from feet to oar (Caplan and Gardner, 2010). Knee extension is followed by a posterior rotation of the trunk, with core musculature engaged to maintain force transfer, before a final drawing of the hands toward the body at the position known as the finish. The athlete returns to the catch position in the recovery with timings and sequencing of movement distinct to that of the drive phase. The primary difference in timing of the stroke from low to high intensities is the ratio of the recovery to the drive phase, decreasing from 3:1 to 1:1.

Figure 1-2: Free body diagram of athlete at catch position
Used with permission from Kleshnev (2011)

The only way for the athlete to generate propulsive power is to apply force to the boat via the feet, with the handle being the only point of leverage. Technical coaching and physiological development is focused on maximising this transmission of force between the handle and the feet.

During the rowing stroke the trunk must act as a rigid lever to transfer the forces primarily generated through the extension of the legs and trunk. Using this foundation, the rigid trunk
allows the arm draw to finish the stroke, whilst maintaining a connection from the feet to the handle (Baudouin and Hawkins, 2002). Hofmijster et al. (2008) demonstrated the importance of maintaining a stiff connection between the hips and oar to allow the transfer of forces produced at the feet. The trunk is a large flexible system encompassing the pelvis and many spinal segments and is capable of numerous articulations. For this system to act as a rigid link it must be stabilised by the musculature of the trunk; weaknesses in these structures around the spine can lead to outputs of the major muscle groups not being transferred effectively into propulsive force (Baudouin and Hawkins, 2004).

1.1.1 Injury in Rowing

The incidence of injury in rowing was generally not considered to be significant until Stallard (1980) observed an increasing incidence of lower back pain in competitive athletes. New rowing techniques, featuring increased flexion and rotation of the spine produced higher performances in addition to increased reporting frequency of lower back pain. The observation of the prevalence of spinal musculoskeletal injuries in rowers continues to draw attention in research and consideration by sporting institutions, coaches and athletes.

Winzen et al. (2011) assessed 67 elite rowers during a 12-month period, presenting the proportion of athletes that had missed training or visited a health professional due to an injury, segmented by body part; 50.0% of subjects reported injuries in lumbar spine/buttock, 33.9% in the shoulder girdle, 32.2% in the forearm/hand, 31.6% in the cervical spine and 28.1% in the thoracic spine. “Overuse” was the most frequently reported reason for injury in all regions of the body, concurring with Smoljanovic et al. (2015) report which noted that chronic injuries accounted for 73% of all reported injuries in a study of 634 elite rowers. The lower back, thoracic spine and pelvis were 3 of the top 5 sources of injury for all competition classes of international rowers questioned. Wilson et al. (2012) reported that 50% of rowing injuries occurred to the spine.
1.1.2 Technical changes to improve performance, with a secondary influence on injury risk

The complicated combination of timing and sequencing that forms the rowing stroke, in addition to the prevalence and type of injuries in the sport of rowing has led to a desire to understand factors and mechanisms that can influence performance outputs, whilst also aiming to reduce risk of injury. Reducing injury risk also acts as a performance goal, as time away from training or competition reduces potential for improvement or competing.

1.2 Rowing technique, performance and kinematic measurements

Rowing training time is split between on-water rowing, ergometer rowing and strength and conditioning work. An ergometer, Figure 1-3, is a training tool that replicates the rowing action experienced on water, but is a stationary, portable device. The most commonly used version is that produced by Concept 2 (Concept2, Morrisville, USA), which allows an athlete to perform the rowing stroke using the same sequence of movements as that during on water rowing. It shares a sliding seat, plates upon which the feet can be strapped, and a handle, replicating that of an oar. A screen displays feedback of power output and session timing, allowing an athlete to practise technique, develop physiology and test performance.

Macfarlane et al. (1997) and Schabort et al. (1999) demonstrated a low variability of performance between rowers and a high retest correlation during 2000 m ergometer time trials. Ergometers are a widespread and regularly used training tool amongst the rowing population, allowing physiological and technical development to improve on-water performance (Nolte, 2011). Assessment in a laboratory using an ergometer provides a repeatable method of measuring rowing performance parameters and technique in a closed, controlled environment.
Athletes seek to employ the optimum rowing stroke, in the absence of a precise definition. As such opinion and guidance from coaches and sporting professionals (Thompson, 2005, Nolte, 2011) offer only descriptive suggestions of optimal technique. When testing rowing performance, the time to cover a known distance in a boat or using an ergometer is the most important predictor of race performance. However, no information on the contributing aspects of technique to this performance measure are routinely available during, and after the test.

Biomechanics uses kinetics and kinematics to describe the forces acting on the human body and their effects. In a sporting environment the way in which an athlete moves can be described with these techniques. Kinematics describe the motion of points, groups or systems with respect to time. They are quantified as three dimensional angles, positions, velocities and orientations. Kinetics is the study of the forces and torques acting on the body internally and externally. The aspects of technique that form the rowing stroke can be described through kinematic measurements, while kinetics can describe the cause of this motion. If kinematic measurements are also made during a performance trial, the influence of technical aspects can be observed and assessed. In rowing an athlete is able to exert force upon and receive inputs
of force through the feet, seat and handle. Kinetic measurements of these forces can further describe the influences of technique.

Different methods of sequencing the execution of the rowing stroke has been shown to change performance outputs (Hofmijster et al., 2008), efficiency and transfer of power from lower to upper limbs (Baudouin and Hawkins, 2002, van Soest and Hofmijster, 2009, Hofmijster, 2010), variations in spinal kinematics (Bull and McGregor, 2000) and potential injury risk (Stallard, 1980, Teitz, 2002, McGregor et al., 2007).

Kinematic and kinetic measures have been shown to be subject to variation by and between individual subjects and groups. Influential factors have been shown to include: experience level (Smoljanovic et al., 2009), gender (McGregor et al., 2008), intensity of exertion, (Buckeridge, 2013, Murphy, 2009) and fatigue (Pollock et al., 2012). Changes in kinematics were observed between low and high intensity activity (McGregor et al., 2005), while longitudinal changes of kinematics have been observed at low intensity (Holt et al., 2003) and in simulated race conditions (Pollock et al., 2009).

Technique has been shown to be influential on performance during rowing, and methods of biomechanics have been applied to identify kinematic measures of aspects of technique that are influential on performance. Specific factors have been found to influence the variations of aspects of technique and performance parameters. This emphasises the value of providing the means of monitoring and observing the kinematic measures that describe these aspects of technique. As injury of the lumbar spine is prevalent in the rowing population, research has also aimed to investigate risk factors for these type of injuries.
1.3 Performance predicting kinematics

1.3.1 What measurements are ‘performance predictors’

Having measured the kinematics of an athlete’s lumbar spine, pelvis and right lower limb, in addition to kinetic measures of handle and seat force, Murphy (2009) assessed which measured variables were most useful in predicting rowing performance, and which discrete aspects of technique could positively affect these variables; 42 elite athletes (defined as international representation in the sport) attended one or more testing sessions over a 26-month period, in a protocol of increasing intensity, providing 1115 datasets. Athletes were male or female, heavyweight or lightweight classification. Using statistical analysis, five main predictors of higher performance outputs were calculated to be:

1. The finish (end of power production) occurring later in the stroke
2. A rapid rate of handle force production
3. High stroke length
4. Large power output
5. Suspension of body weight away from seat

The analysis showed these predictors to be positively affected by the following:

1. Minimal flexion of the lumbar-pelvic joint (L5/S1, defined as the angle of the 5th lumbar vertebrae with respect to the sacrum) at the catch position.
2. Minimal flexion of L5/S1 at a position between the start (catch) and finish position where handle force is maximal (MHF)
3. Minimal flexion of L5/S1 at the finish
4. Large knee flexion at the catch position (i.e., knee compression)
5. Inferior ankle joint centre at the finish position (i.e. heels down at finish)
6. Superior ankle joint centre at the catch position (i.e. heels up at catch)

Predictors 1-3 state that minimal flexion of the lumbar-pelvic joint throughout the rowing stroke is a positive predictor of performance during ergometer rowing.

The influence of these predictors implies that these are the aims for athletes to improve or maintain in order to maximise performance. As discussed in this chapter, the lumbar spine is
an area with a high incidence of injury in the rowing population. This compounds the relevance of such performance predictors, as these kinematics may have implications on injury risk. This likelihood of risk is suggested by comparing specific kinematic and kinetic measurements in rowing studies to the same measurements identified as risk factors in epidemiological studies of other populations as close to that of an athlete as possible.

1.3.2 The relationship between kinematic performance predictors, performance and injury risk

Epidemiological studies of injuries in industrial manual labour workers have been undertaken to identify kinetic and kinematic factors that increase likelihood of injury for a group which experience high volumes of physiological activity, traits shared with that of competitive athletes. A resource of understanding potential limitations of the human body in dynamic activity with respect to kinetic and kinematic measures can be made by combining such epidemiological studies of risk factors (Adams et al., 2006) with mechanical studies of the properties of the human body (Panjabi et al., 1976). This resource can be used in the absence of literature on risk of injury in a sporting environment with respect to observed and suggested maximal and cyclical kinetic and kinematic measures. Whitesides Jr (1977) suggests the most important forces and moment for the spine are compressive forces, tensile forces and axial torque, however the majority of research in a relevant sporting environment primarily discuss values of compressive loading.

During on-water rowing compressive loads at the lumbar-sacral junction have been calculated to reach 5500 N (Munro and Yanai, 2002), while in ergometer rowing this can be up to 2700N (Reid and Mcnair, 2000, Buckeridge et al., 2012). These studies expressed the limited accuracy of their measures, and were calculated with variations in methods and assumptions. However these calculated values were all within the 2000-14000N range of loading absolute limits described by Adams et al. (2006), while the 5500N loading of one study exceeded the loading limit recommendations of Waters et al. (1993). Adams et al. (2006) suggested that fatigue damage for spinal segments to occurs when compression loads are greater than 4000 N, approximately 40-50% the maximal failure load. However, during lifting tasks this value varies significantly due to the weight lifted, distance and speed of
movement. Granata and Marras (1999) suggests that compression loads greater than 6500 N to double injury risk, when compared to 2000N as illustrated by Figure 1-4.

![Figure 1-4: Probability of occupationally related low-back pain disorders for calculated dynamic spinal loads](image)


Compression force has formed the basis of most injury risk studies and loading limit recommendations, such as the National Institute for Occupational Safety and Health (Waters et al., 1993) suggest a limit of 3444 N. However, as demonstrated in Figure 1-4, load is not in a linear relationship with risk for compression alone, with the authors suggesting that injury due to one factor (e.g. compression) is unlikely, instead this is likely to have been generated by combinations of multi-dimensional loads (Granata and Marras, 1999). A component of this multi-dimensionality is shear loading, with values of 660 N calculated during ergometer rowing (Reid and Mcnair, 2000); this exceeds the shear force of 500 N observed in manual labour studies (Adams et al., 2006, Adams and Hutton, 1981). Gallagher and Marras (2012) suggests that for a healthy individual of working age, shear loads of 700N to be tolerated for no more than 1000 cycles per day. Elite rowing athletes perform up to 1600 strokes in a 18km training session at 20 strokes per minute.
Repetitive compressive loading of the lumbar spine has been found to considerably increase the risk of back pain (Parkinson and Callaghan, 2007). As a sport featuring cyclical movement, exhibiting approximately 1800 trunk flexion cycles during a 90-minute rowing session, repeated application of load occurs regularly. Injuries may result from cumulative micro trauma through fatigue, or from a single application of high magnitude loading. In addition to tissue failure at high or repeated loading, application of unstable load increases risk. Unstable loading can expose the loaded joint to sub-optimal movements, potentially with high rates of change of velocity and loading, contributed by poor motor control and proprioception of movements. The complexities of risk for the spine is illustrated in Figure 1-5 (Cholewicki and McGill, 1996).

**Figure 1-5: Injury risk and loading model by Cholewicki and McGill (1996):p.8**

Cholewicki and McGill (1996):p.8 suggest injury risk to the spine can be due to tissue failure or instability. High loads can cause tissue failure. Instability or cyclical application at low loads may cause local joint movement sufficient to overload soft tissues.

This would suggest that high volume of training may be related to injury, however, this has not been established as a significant predictor of risk. Wilson et al. (2010) observed that an increase in time spent in ergometer training was significantly associated with risk of lumbar spine injury and Teitz (2002) showed that ergometer sessions longer than 30min were a significant predictor of lumbar spine injury. While associations have been made between
lumbar spine injury and volume of weight training (Budgett and Fuller, 1989, Reid et al., 1989, Coburn et al., 1993), and with general volume of training (more than seven sessions per week) (Smoljanovic et al., 2009), neither general volume or weight training volume has been established as significant predictors of injury in the lumbar spine. This suggests that an individual athlete’s technique, and its variation, especially on the ergometer appear to have more significance than volume of training. Establishing influential factors on injury risk is sufficiently complex as to make current research undertaken underpowered and subject to excessive variation. In light of this, risk factors such as those introduced by Granata and Marras (1999), Cholewicki and McGill (1996), are used as guidance for kinematic studies where such information is not available.

In a maximal indoor rowing trial, Caldwell et al. (2003) noted that lumbar flexion increased from 75 to 90% of maximal range of motion with fatigue, concluding that muscle fatigue in the erector spinae muscles causes excessive lumbar flexion. Flexion above 75% of the maximum range of motion considerably increases stress on the intervertebral disc (Dolan et al., 1994), and as such, combined flexion and compressive loading has been identified as a mechanism for injury to the lumbar spine structures (Gallagher et al., 2005). It has been observed that depending upon the lumbar level, spinal ligament damage occurs in flexion between 5° and 20° (Adams et al., 2006). Murphy (2009) observed average maximum L5/S1 flexion of 11.8° (±10.6°). Frontal plane rotations, in addition to sagittal flexion, increase injury risk in industrial studies, and such combinations have been demonstrated during ergometer rowing (Wilson et al., 2013). Panjabi et al. (1982) showed disc prolapse to be induced when sagittal flexion was combined with moderate compressive loading, with these mechanisms linked to lower back pain in rowers (O’Sullivan et al., 2003).

The previous section discussed factors that influenced variability of technique. Buckeridge et al. (2012) found elite athletes to exhibit increased flexion of the lumbar spine during higher intensity exertion, in addition to increased loads and moments calculated at the L5/S1 junction. This increase in load was not reflected in increased propulsive force at the foot stretcher. It could be hypothesized that increasing performance will increase loading of the body and therefore injury risk, however, this relationship will be significantly affected by the quality of movement that achieves this increase in performance. Furthermore, Buckeridge et
al. (2012) demonstrated a deleterious change in quality of movement to increase loading (and therefore potential injury risk), at no benefit in terms of performance.

The effect of fatigue on electromyography of trunk musculature during a 2000m race simulation was not shown to be significant by Pollock et al. (2009), however trunk kinematics did change. This was in addition to degradation in power and stroke length (two of the five predictors of performance by (Murphy, 2009). Pollock et al. (2009) suggests two changes to be related to general fatigue, with motor control strategies using the trunk more actively to maintain power, despite this exhibiting less effective performance.

Groups of observations suggest that cyclical flexion, particularly when combined with fatigue, may alter joint mechanics and loading patterns of the spine, leading to risk of tissue failure and resulting injury (Adams and Dolan, 2005, Caldwell et al., 2003, Holt et al., 2003, Parkinson et al., 2004, Mackenzie et al., 2008). It has been demonstrated that athletes are subject to changing their technique based on multiple factors. Buckeridge et al. (2012) demonstrated increases in peak loading at the junction of L5/S1 alongside increases in lumbar-pelvic flexion, and hypothesised that there was a relationship between the increased loading observed and deleterious changes in technique. Examples of such changes in technique during the drive and at the finish are illustrated in Figure 1-6.

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**Figure 1-6: Diagrams of techniques during mid-drive and finish with lower and high loading calculations**
1.4  Application of biofeedback

Biofeedback is a method of providing information on a process being undertaken through physiological or biomechanical measurements. It has been demonstrated that visual feedback can be beneficial during rowing training (Page, 2003), for elite athletes and their coaches (McGregor et al., 2015). This information allows individuals to monitor and modify the process in response to the feedback received, giving accurate control of that function, in comparison to self-perception alone.

Some of the predictors of performance found in the literature discussed in this chapter concern kinematic measures that can be applied as guidance to change and aim to improve technique or performance. Biofeedback provides subjects with live information or sensory warnings or acknowledgement in response to a subject’s movements. Biofeedback also allows for measurements to be continuously monitored, in addition to being recorded, for later comparison between individuals, groups and longitudinally. This provides a means by which to monitor the influence of factors demonstrated in literature such as variability with fatigue and intensity of effort.

1.5  Three dimensional kinematic measurement equipment

Kinematic measurements are acquired through motion tracking equipment that can provide a description of the position and orientation of its marker(s). This information can be made using two-dimensional (2D) video analysis (Elliott et al., 2002) or three-dimensional (3D) motion with electromagnetic or optoreflective systems (Hassan et al., 2007). The location of placing the tracking markers on subjects in kinematic motion tracking is standardised to known body landmarks or clusters on the human body (Wu et al., 2002). These landmarks can be identified repeatedly and reliably through the method of palpation (Snider et al., 2011) and are considered to feature minimal skin movement relative to their skeletal landmarks (Shaheen et al., 2011). Clusters can be used on body segments and their position relative to landmarks known through digitisation.
The accuracy and range of kinematics that a system can track are proportional to their complexity and cost. Acquiring three dimensional kinematic measurement of a closed chain activity such as rowing requires:

1. Appropriate equipment – available to use, with validated instrumentation suitable and reliable in the chosen environment. Must also be suitable for the subjects being tested and those performing and managing the equipment.
2. A specific protocol – where the subject, equipment and measurement space is prepared within the requirements of the measurement systems.

The results produced from the equipment must then be processed in an appropriate manner to provide the desired kinematic data. This data must be understood by those who manage and operate the equipment, and then be presented in a manner relevant to the recipient of the data. For example, the aims, technical understanding and areas of interest for an athlete, coach or an engineering research journal are significantly varied. Surface marker placed motion tracking is an established method of acquiring kinematic measurements, however, the cost and complexity limit the number of individuals that can acquire the information, the environments in which acquisition can occur and the number of individuals that be monitored and assessed using kinematic measurements.

1.6 Conclusion: the relevance of performance predicting parameters

Literature discussed in this chapter has calculated estimates of loading levels within joints or body segments during rowing, and compared them to injury risk studies on similar kinematic movements outside of a sporting context. In these risk studies, loading and flexion of the spine, in terms of peak values and cumulative cyclical exposure are suggested to be significant factors of risk. Rowers have been demonstrated to exhibit high sagittal plane flexion and repeated cyclical loading during various levels of exertion and fatigue, factors that contribute to the variability of technique. The combination of these factors has been cited in studies of trunk fatigue as risks for lower-back injury. Volume of training in competitive athletes has been shown to not act as a predictor of injury risk, therefore aspects of technique may exert influence on injury risk.
There is no explicit causal relationship for injury in the context of rowing, and the vastly complex and extensive task of attempting to establish this means that risk of injury is a consideration, whilst influences upon performance can be determined. The type of motion, or technique described in the list of discrete predictors of performance by Murphy (2009) are pertinent to assess and observe how athletes perform with respect to performance. In combination with injury risk studies in other contexts, the potential consequence of such technique can be considered.

Monitoring of this technique during rowing training and racing as biofeedback as well as longitudinally is likely to be beneficial by minimising changes in technique (such as increased flexion in the lumbar spine, observed in fatigue and intensity step protocols) found to be deleterious to performance.

The acquisition of descriptive measures of rowing technique requires complicated and expensive systems featuring motion tracking and force measurements. There is scope to access the relationship between the measurements that are known predictors of performance, measured in three-dimensional space, and those that could be measured using less complex methods. Establishing these relationships may allow for assessment of athlete’s technique to be made with less complex equipment, allowing more individuals to assess quality of their movement with respect to the performance predictors suggested in rowing research literature.
1.7 Project Aims

I. Improve performance in ergometer rowing by developing, collecting and analysing kinematic measurements to determine influential parameters

II. Determine if any kinematic measurements have not been utilised, and if a valid and novel measurement would add to the understanding of ergometer rowing, to develop and validate a means of doing so

III. Test the hypothesis that kinematic and kinetic measures that normally require instrumentation of the athlete can be predicted with an instrumented ergometer alone

1.8 Development of Objectives

1.8.1 Introduction to instrumented ergometer

This study is the latest in a line of work undertaken at Imperial College since 1998, developing the kinetic and kinematic understanding of the rowing stroke. This work could not exist without its predecessors and many of the methods and analytics will form a foundation upon which this study shall build. An instrumented ergometer, Figure 1-7, is a key device in this research.
Real time biofeedback

Handle force and motion

Forces at Feet

Flock of Birds motion capture

Seat force and COP

Figure 1-7: Testing system, motion capture and kinetic instrumentation
Inset images (Murphy, 2009) illustrate the motion capture system equipment, instrumentation at the head of the machine, the handle and the seat.

The ergometer is instrumented at the handle with a uniaxial load cell (ELHS, Entran, Lexington, USA) to measure the force at the handle with a range of 2500 N (Loh et al., 2004). The flywheel of the ergometer is fitted with a linear encoder (ERN120, Heidenhain. Traunreut, Germany) to measure stroke length, (Loh et al., 2004). The ergometer foot-stretchers have been replaced with strain-gauge instrumented footplates (Chee, 2006 , Buckeridge et al., 2012), to measure vertical and horizontal forces in addition to longitudinal centre of pressure. The seat is instrumented with four uniaxial load cells (ELPM, Entran Lexington, USA) to measure vertical forces on the seat, and the centre of pressure upon the seat (Murphy, 2009).
Kinematics are captured using a Flock of Birds (FOB) motion tracking device (Ascension Technology, Burlington, USA) that consists of an electromagnet transmitter, and four receivers, designated S1 to S4. Each receiver consists of three orthogonal coils; the intensity of the voltage or current of these coils allows the FOB processor to calculate the range and orientation of the receiver relative to the transmitter. This produces three dimensional translation and rotation of the receivers within the tracking volume. The system tracks the motion of the right foot, right leg, pelvis and lower back. Digitisation and post processing methods provide the trajectories of discrete locations of the athlete (landmarks) not directly measured with the 4 sensors. The equipment and methodology has been validated to be suitable for kinematic motion tracking of spinal and lower limb motion, providing sagittal plane rotations to ±1° of MRI measurements (Bull and McGregor, 2000). The arrangement of the equipment in a laboratory and relative to one another was optimised by Murphy (2009), calculating an average discrepancy between a measured vector between two sensors of 8.37 mm, with a standard error of the mean difference being 0.55mm.

1.8.2 Instrumented ergometer outputs

For analysis, data is processed from a combination of calculations, and non-performance data recording. These methods are described in Murphy (2009), and were utilised in this study, are described in Chapter 3.

These measures can be summarised as 3D kinematic variables and non 3D kinematic variables as presented in Table 1.1.
Non 3D Kinematic Variables
Handle force
Seat Forces
Foot Forces
Handle position
Seat Centre of Pressure Coordinates
Time Stamp
Athlete mass

3D Kinematics
Positions of FOB markers
Angles of FOB markers
Positions and relative angles of body segments, calculated in post processing

Table 1.1: Summary of instructed ergometer outputs

The non-three dimensional kinematic variables require relatively less complex equipment, protocols, data processing and analysis than the athlete kinematic measurements. The value of discrete kinematic variables for performance monitoring and analysis have been demonstrated in previous sections, however the 3D motion capture systems used to acquire such measures are not feasible for widespread use in routine training, testing and competition by non-specialists. This restraint limits the opportunity to monitor or improve athlete’s technique to those that can access such equipment and use it regularly.

Studies have used measures of handle force and displacement to analyse performance, fatigue and the differences in ergometer design (Bernstein, 2002, Caplan and Gardner, 2005, Colloud et al., 2006). Smith and Spinks (1995) used four independent measurements to design a predictive model that could identify novice, experienced and elite athletes with a 83% success rate. In squat performance testing, linear positional transducers are used to replicate the outputs of ground reaction force platforms, with consistent and reliable comparative outputs demonstrated by Hansen et al. (2011), however a sufficiently developed model must be created to avoid inconsistency when data is used to derive the profile of a value over time. In a rowing application the Powerline system (Peach Innovations, Cambridge, UK), includes measurements of force at the feet and handle (indirectly via resultant force in an instrumented oar pivot), as well as measures of handle position (via the angle of the aforementioned pivot) and seat position. The use of these measures is primarily for synchronising members of a rowing crew during on-water rowing, however, if found to predict kinematic variables, would be valuable for performance monitoring.
1.8.3 Ergometer Seat

In the instrumented ergometer system discussed above, the position of the seat is not recorded. Knee compression was found to be a predictor of performance by Murphy (2009), and in technical coaching, compression into the catch can be described as bringing the seat to the heels of the feet. Seat position could be used to predict knee compression, or calculated if combined with anthropometric information. Thompson (2005) suggests that the movement of the handle and the seat are ideally simultaneous and identical for maximal efficiency of force production, with poor co-ordination of movements wasting propulsive force. A common technical error in rowing is to ‘shoot the slide’, this is when the seat (Figure 1-3) of the rowing boat or ergometer visibly moves backward quickly with little or no productive movement of the handle, and comes about when the body is allowed to collapse and transfer minimal load from the feet to the handle. In addition to lower propulsive force and performance outputs, technical flaws such as this were shown to produce variations in spinal kinematics by Bull and McGregor (2000).

The study of (Buckeridge et al., 2012) used an inverse dynamics model to calculate joint loads, and this study calculated that deleterious changes in quality of movement increased loading at no benefit in terms of performance. Inverse dynamics is a method for computing intersegmental joint forces and moments of rigid bodies, calculated from kinematics and mass-inertial properties of the body segments to be analysed. A limitation of studies with calculated joint loading during ergometer rowing such as Buckeridge et al. (2012), Reid and Mcnair (2000) is the position of the seat (and thus the forces between the seat and body) has either been estimated or ignored. A means of quantifying seat position would enhance future calculations of joint loading in ergometer rowing and discussion on the contribution of technique to these loads.

The ergometer seat, in addition to the ergometer handle and footplates, are the only three points of an ergometer or on-water rowing boat that the athlete interfaces with during the rowing stroke. Visual observation and coaching of an athlete includes their body, as well as the movements of the seat, handle (which in on-water rowing dictates the movement of the oar) and feet. Verbal cues are used to assist athletes with technique by suggesting different
types of movement or forces to be applied at these three points. Commercial systems, as well as biomechanics research, as discussed in Chapter 1, have measured the position of the handle, the forces at the handle, feet and seat, but not the position of the seat.

1.9 Hypothesis

I. Quantifying the position of the ergometer seat during the rowing stroke will enable an assessment of its significance of influencing performance outputs.

II. In combination with other non-kinematic measures, it is hypothesised that seat position may contribute to a model that can predict three dimensional kinematic variables.
   o For example, joint angles of the hip, knee and lower back have been shown to describe an individual’s technique and to be significant predictors of performance outputs. By using measurements only on the ergometer, such as handle position and force, seat position and force, an athlete’s technique could be predicted, without direct measurement of these three-dimensional kinematics.

1.9.1 Proposed Outcomes

It is anticipated that a relationship will be found between variations in indoor rowing technique and variations in position of the seat at key points in the rowing stroke.

The three points of interaction between the athlete and ergometer; seat, handle, footplate are the only points through which variations in athletes and their technique can influence performance. This study will for the first time consider the movements and forces at these three points and quantify their relationship with aspects of technique that occur between them.

Observing and developing the variations of movement between these three points, i.e. the way the athlete moves the body, is the role of coaches, however the movements and their timing can be too fast to accurately observe and assess in real-time. It is anticipated that this study will quantify how the movements and timing of the three points of athlete interaction
influence performance outputs at the catch and during the drive of the rowing stroke. The output will be to improve athlete performance by increasing the effectiveness of coaching and accessibility to receive it. The knowledge of the relationships between seat, handle and performance will influence coach and athlete foci, and if such measurement systems of seat and handle position, simplify the process of improving performance. This simplification would route from both providing quantifiable information to assist coaches, but also providing the opportunity of feedback and performance improvements to athletes otherwise without access to coaching.

It is anticipated that the relative movements and the timing of the seat and handle will indicate the transfer of propulsive force from the handle to the feet, and thus performance outputs. For example, if the handle moves faster and earlier from the catch than the seat, and with low force applied to the handle and footplate, then the technique utilised has been less effective in producing performance outputs than if the handle and seat move together from the catch position. The secondary output of this sub-optimal movement the inherent joint flexions and extensions that produced it are in some instances, such as the hip and lumbar spine, also associated with increased injury risk as well as reduced performance outputs. As improving performance outputs and technique of movement is the role of coaches in rowing, the seat, handle and feet measurements will quantify aspects of rowing coaching.
1.10 Study Objectives

1. Instrumentation and calibration of seat position measurement
   i. Identify design requirements and specification
   ii. Design solution
   iii. Test accuracy and validate solution
   iv. Check for reliability in application
   v. Integrate and synchronise with kinematic and non-kinematic measurements

2. Data Acquisition
   i. Select test protocol and subjects
   ii. Acquire data using new and existing kinematic and kinetic measurement systems
   iii. Process data

3. Describe the motion of the seat during ergometer rowing
   i. Describe motion and identify points of interest
   ii. Investigate variance between groups and protocol step

4. Analysis, with respect to study aims and hypotheses
   i. Study the interaction of non-three dimensional measurements with ‘performance parameters’ on discrete level to identify influential parameters
   ii. Investigate opportunity to predict performance parameters using ergometer instrumentation alone
Chapter 2   Instrumentation and Calibration

This chapter describes the design, development and validation of a new kinematic measurement device to identify and record the movement of the seat on a rowing ergometer. The design criteria of requirements and constraints are outlined before the selected design is identified and described. It is validated and integrated with a system of kinematic and kinetic instrumentation to provide new measurements used to assist in the meeting of the aims of the thesis.

2.1 Development of instrumented seat: Design

2.1.1 Design Criteria

The following design requirements and constraints were selected:

i. Accuracy and Reliability
   o Selected design should be as accurate and consistent in its accuracy of measurement as possible. However, this must be viable in the context of regular subject testing, minimising the required frequency of (re)calibration and in balance with data processing cost and time. Accuracy and reliability must be assessed and quantified, with an average error of less than 5mm required.

ii. Minimise impact to the subject using the ergometer, i.e. a non-invasive solution
   o Solutions that physically contact subjects or apply force or pressure to the ergometer components may influence measurement outputs, or the comfort of the subjects.

iii. No electromagnetic interference of local electromagnetic motion tracking system.
   o The FOB is an electromagnetic motion capture system, sensitive to magnetic fields.

2.1.2 Design Development & Rationale

The ergometer seat is constrained to translate along a fixed track of 1100mm length, using wheels mounted to the seat, both above and below the track, effectively constraining the seat
in all but one dimension of translation, and no rotation. It is possible to mount equipment to both the seat and the track.

Commercially, seat sensor measurements for indoor rowing are not available, however on-water systems, such as the Powerline system (Peach Innovations, Cambridge, UK) utilise a magnetic hall sensor. This system installs a magnet on the seat, and a rail of numerous hall sensors along the path of travel. This forms part of a series of non-three dimensional kinematic measures in the Powerline system. A hall sensor operates by producing a voltage output when in the proximity of a magnetic field, the resolution of this method can be customised but due to the size of the magnets, is limited to 20mm. This resolution limits the accuracy of the data, and thus, in addition to the sensitivity of the FOB motion tracking system to external magnetic fields, this example and methodology does not meet the design criteria for this study.

A rotary encoder could be used to provide ergometer seat position. This could be an encoder fixed externally, connected to the seat via a cable under tension, where movement of the seat would extend or return the cable, and the encoder signalling this change. A rotary encoder could also be mounted on the seat, for example integrated with the ergometer seat wheels to signal rotation and this can be processed to calculate seat translation. To achieve an accuracy of at least 5mm, considering the size of the wheels, and the maximum rowing cycle frequencies of 35+, the wheels will rotate from 6-21 revolutions per seconds, requiring a device frequency of 140-460Hz. However a rotary encoder would apply a force to the seat, such as the aforementioned cable solution, which must be under tension to function, or an instrumented seat wheel would rotate with different properties to that of a standard ergometer seat. Davoodi et al. (2002) used a rotary encoder for seat position in a rowing application, where paralysed subjects operate an ergometer through electrical stimulation, however in this case passive measurement of the subject is not a consideration. Finally, a cable or seat mounted encoder may impact on the usability of the machine, with a seat mounted encoder or external encoder and wire being exposed to potential damage when a subject mounts or dismounts the ergometer in varying states of fatigue.
Alternative non-mechanical and non-interference solutions are optical. An optical solution offers the benefits of not interfering with the equipment, and could be manufactured to be integrated into an ergometer seat, away from potential damage. Gravenhorst et al. (2014) utilised an affordable ultrasound emitter for ergometer seat measurement and suggested reliable results; the author states a maximum slide velocity error of 30%, with max displacement error likely to be greater (but not given by the author), caused in part due to the delay in measurements. The sensors used have a long and variable level of latency, producing a best-case sampling speed of 100ms, and while the paper quotes a 160Hz theoretical maximum, at 100Hz the delay is still significant, thus not providing live data for seat position. Gravenhorst’s proposal to reduce error is to average over multiple strokes as the data is recorded, making this solution inappropriate for using in the desired application where it is required to compare instantaneous seat position with other instantaneous data. Therefore, for measurement resolution, relevance and accuracy of data, this solution is not viable. Gravenhorst also compared the ultrasound data against a video capture system, however this is not a live solution, with all data produced in post processing.

An optical solution offers the potential to meet the design requirements, therefore the potential of an optical solution will be explored in more detail.

2.1.3 Design Proposal

Optical emitters and receivers, mounted to the ergometer seat, in combination with a reflective surface mounted on the ergometer rail, can provide measurement of the position of the ergometer seat, or measurements that could be processed to calculate this.

The seat velocity and hence measurement frequency, in addition to the length of the slide limits the use of a solution where unique marks are fixed along the slide

2.1.4 Selected Design

The selected solution that meets the specified design requirements is an optical method where sensors are mounted to the seat of the ergometer, and a track of reflective material is mounted on the slide, upon which the seat is mounted and constrained to move along.
The collective seat sensor is a custom-made unit, comprised of two reflective object sensors, mounted to a plate, which is encased for protection and affixed via two mounting bolts to the ergometer seat.

The optical sensors chosen are Optek OPB704W Reflective Object sensor (Optek Technology, Inc. Texas, USA. Datasheet in Appendix A), and the reflective material is MC-PET Microcellular Reflective Sheet (Furukawa Electric Co. Ltd. Tokyo, Japan. Datasheet in Appendix B). The sensor consists of a light emitting diode and a silicon phototransistor, where the phototransistor only responds when a reflective surface passes within the field of view.

Two sensors are mounted to the ergometer seat facing a track of reflective markers. Each marker is spaced 6mm apart, from centre to centre, and each sensor mounted on the seat produces a signal when the reflective track passes. By mounting the centre line of each sensor offset from one another by 2mm, the system effectively becomes a two-signal linear encoder, as demonstrated by ‘Channel A’ and ‘Channel B’ in Figure 2-1. By monitoring which sensor produces a signal first as they pass over a marker, say X to Y the direction of movement can be determined.

![Diagram](image.png)

**Figure 2-1: Illustration of interpreting direction from two signals**

If Channel A produces a signal before B, the measured movement is positive, if B before A, then a negative movement.

To avoid noise, influencing other measurement systems, and to ensure a strong discrimination between positive and negative signal inputs, a co-axial cable with a ground connection is
employed. The cabling uses a twisted pair method to attempt to avoid electromagnetic interference from other sources, whilst a harness shields from mechanical interference.

The track of markers comprises of a 1000x200mm sheet of MC-PET, affixed by 3M spray adhesive to a thermoset nylon sheet 1000x250x5mm, with slots in the nylon sheet to provide the consistent spacing of reflective and non-reflective surface required. The design of the nylon sheet was completed in a computer-aided design package SolidWorks (Dassault Systèmes, Vélizy-Villacoublay, France) and then manufactured using computer numerical control (CNC) machining in the RSM Workshop in the Royal School of Mines at Imperial College. This was completed by Mechanical Workshop Technician Mr Daniel Nardini, after adjusting the CAD model using his design for manufacturing considerations, the nylon sheet was split into two to speed up the CNC process, and the radii of the slots adjusted.

The output signal is sent to a data capture system, LabView (National Instruments, Texas, USA) via a National Instruments NI9401 module (National Instruments, Texas, USA) and processed using a customised processing script in LabView software, see Appendix C. The sensor as installed in prototype form can be seen in Figure 2-2.
2.1.5 Design Development note on changes of direction

The initial design of optical sensor featured a single optical sensor, with a track of markers unique to each position along the track. In this design, the sensor would read each unique marker and via processing, deduce the exact position. However it was not viable to produce
200 unique markers (to provide a resolution of 5mm along a 1000mm track) that could be observed by the sensor at frequencies over 100Hz. Moving to an optoreflective solution where the track features sufficient marker spacing and thus resolution, leads the observation to be indirect, the sensor does not know exactly where the seat is, it can only provide information on a change in reflective or reflective state of the track it is observing. If a single optoreflective sensor is thus used, the sensor could only provide scalar information without a direction component. Thus two sensors offset from one another could be used to provide two signals, and thus a two signal encoder.

It was considered that without sufficiently comprehensive processing logic, or if a marker was missed due to obstruction for example, the signal could drift, by missing a change of direction or erroneously calculating a change of direction had occurred. Thus it was designed for a third optoreflective transmitter and receiver to be put in place, mounted over a track with a single reflective point, mounted close to the centre of the ergometer, thus independent of individual seat position due to subject technique or anthropometrics. This single point produces a single signal each cycle, which can be used as a reset point, where if the calculation of position from the two offset sensors does not also correspond to this fixed reset point, the signal is known to have drifted. Thereafter the measurement would reset and continue from the correct fixed point, in addition to providing a warning to the user that a source of drift has occurred. This may be a single unrepeatable error, influencing a single stroke cycle, or in the example of an obstruction in the reflective track, an avoidable issue requiring attention. In both of these examples this dataset can be repaired, rather than potentially discarded if the drift was not accounted for.

The processing logic in LabView included calibration before each subject test, in addition to observing each optoreflective signal, as well as the relative signal timing. This suggested that a third signal would be redundant in a controlled laboratory environment, but validation would confirm or disprove the requirement of the third, anti-drift sensor.
2.2 Validation

Having met the design requirements of being non-invasive upon the ergometer, and not interfering with electromagnetic signals of motion capture systems, the final requirement was to meet an accuracy of measurement of 5mm, and to ensure the reliability of the solution.

2.2.1 Methodology

Initial validation of the system during development was undertaken using a simple solution by constraining the movement of the seat using 3M transpore surgical tape, and a 1000mm metre rule. Sheets of tape were layered atop one another perpendicular to the seat rail, and this was repeated in an identical manner further down the slide, with the seat in between the two points. The distance between the two innermost edges of the lines was marked before the application of tape and confirmed to be 600mm, and the lines applied with a engineers square to ensure they were perpendicular to the rail. The lines of tape were sufficient to constrain the movement of the seat within the 600mm range of travel. One end of the range was calibrated as zero in LabView, and translating to the end range of travel recorded 600mm, in agreement with the metre rule initially used.

To test for drift in of its measurements, a series of trials was conceived to replicate typical and atypical indoor rowing stroke cycles. The seat was constrained to a 600mm range, the scenarios named trial number 1-8 inclusive of Table 2.1 were completed by moving the seat by hand, using an electronic clock to ensure the correct frequencies of movement.
<table>
<thead>
<tr>
<th>Trial number</th>
<th>Duration (seconds)</th>
<th>Number of cycles</th>
<th>Description of movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>20</td>
<td>Consistent, to replicate low intensity rowing cycle</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>20</td>
<td>Consistent, to replicate low intensity rowing cycle</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>42</td>
<td>Inconsistent, to account for abrupt inflections</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
<td>24</td>
<td>Inconsistent, to replicate mid intensity rowing cycle</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>24</td>
<td>Consistent, to replicate mid intensity rowing cycle</td>
</tr>
<tr>
<td>6</td>
<td>180</td>
<td>90</td>
<td>Consistent, to replicate high intensity rowing cycle</td>
</tr>
<tr>
<td>7</td>
<td>180</td>
<td>60</td>
<td>Consistent, to replicate low intensity rowing cycle</td>
</tr>
<tr>
<td>8</td>
<td>180</td>
<td>60</td>
<td>Inconsistent, to replicate low intensity rowing cycle</td>
</tr>
<tr>
<td>9</td>
<td>60</td>
<td>45</td>
<td>Consistent, to replicate high slide velocities and accelerations</td>
</tr>
<tr>
<td>10</td>
<td>60</td>
<td>45</td>
<td>Consistent, to replicate very high slide velocities and accelerations</td>
</tr>
</tbody>
</table>

Table 2.1: Table describing seat position sensor validation trials

The results from all trials produced a total of zero drift both individually, and thus a total drift for the 8 trials of Table 2.1. This validation indicated that a third, anti-drift sensor was likely to be unnecessary in this application.

Having considered the drift of the sensors, an additional validation method was undertaken. The position of the ergometer seat was recorded by the seat position sensors, and simultaneously recorded with a VICON optoreflective motion tracking system (VICON, Oxford, UK). Windolf et al. (2008) demonstrates overall accuracy of positional measurement of less than 221 µm using an operationally identical VICON system. Having validated cumulative position data using a ruler and observing the drift on the system to be zero, VICON would be used to investigate instantaneous measurement and quantify accuracy and reliability.

Optoreflective methods of motion tracking use cameras that emit and receive infrared light to detect spherical reflective markers. When a marker can be detected by three or more cameras, its position in 3D can be quantified and recorded. As individual markers are spherical, individual marker rotations cannot be quantified. However, when three or more markers are used a known distance apart from one another, a plane can be created passing through them, and the rotations of this set of markers recorded.
The angle of the slide (the metal rail upon which the seat is constrained parallel and perpendicular to the direction of seat travel) was measured using a Digi-Pas DWL (Digi-Pas UK, Dundee, UK) and was exclusively 0.0° every 50mm of its length. Considering this, four reflective markers were affixed using adhesive tape to the four corners of the top of the ergometer seat, having marked the placement location for symmetry and consistency. VICON MX was used to capture motion for the four markers. The co-ordinate systems of the motion capture system was calibrated to be parallel and both vertically and horizontally perpendicular to the direction of the slide. The averaged co-ordinates of the four markers on the seat as it was translated was found to vary insignificantly in all but one axis, with no rotations or translations perpendicular, either vertical or horizontal, relative to the ergometer slide. Data was therefore compared between the output of the calibrated seat position sensor, and the averaged co-ordinates of the four markers on the ergometer seat.

Two data capture systems, LabVIEW and VICON MX were used to capture data for the seat sensor and VICON motion capture output, and were captured simultaneously using timestamp data sent through a wired connection between the two systems that also initiated simultaneous recording. The data was then collated into a single data file using the timestamp data. Ten trials of the seat position data were undertaken, described in Table 2.1.

These trials were undertaken to replicate the durations, velocities and accelerations that would be expected during testing sessions from low to high intensity, including examples of strokes per minute and frequency of inflection far higher than would be observed by any rowing athlete during a genuine maximal effort performance.

2.2.2 Results

Statistical analysis was used to compare the seat position data from the manufactured seat position sensor, and that recorded by the VICON motion capture system. The seat position data from the VICON and the manufactured seat sensor is shown in Figure 2-3 for trial 4, 24 strokes over 60 seconds described as ‘Inconsistent, to replicate mid intensity rowing cycle’ in Table 3.5. Visual inspection shows both plots to be similar, and can be quantified by calculation Pearson’s Correlation co-efficient. For all ten trials this was greater than 0.99.
Correlation and regression methods are limited in validity in comparing two methods of measurement, as they summarise data via methods other than their differences. Bland and Altman (1986) propose a method to focus on differences between two methods of measurement. This was applied to all the data for all ten trials. Figure 2-4 demonstrates the mean differences in measurements recorded by the VICON system and the seat position sensor along the length of the tested space.
Mean difference at each nearest millimetre along the length of the measurement region between VICON and seat position sensor. Mean error illustrated is adjusted mean error, as the data region of mean difference less than -3mm was significantly influenced by the extremes of test 10.

The mean error along the length of the slide was -1.55 mm, with a standard deviation of 1.1, and consistently measured less than that measured using the VICON system.

The influence of each test in Table 2.1, and of inflections performed per test was assessed for statistical significance was tested in SPSS (version 23, IBM, New York, USA) to locate and confirm differences. Very high inflections, such as those of Test 9 and Test 10 was found to be of significant influence on the mean error. These tests subjected the seat to 40+ cycles per minute. During on-water rowing, experienced and competitive rowers spend the majority of races at 30 – 36 stroke cycles per minute, but may exceed this at the start and into the finish of a race (Nolte, 2011). Test 9 and 10 were removed from the Bland-Altman comparison and the mean error was found to be -1.05mm, standard deviation of 1.0. As the Bland-Altman compared travel in both directions for 8 trials, direction of travel was not an influence of.
error. The mean error was assigned as a constant in LabVIEW for future applications, the source of which is due to the inherent design of the system, as the sensor is comprised of two optical receivers, with change of position determined by observing which receiver signals before the other. Therefore, the mean error of \(-1.05\)mm, when adjusted through the assignment of a constant, results in the calibrated seat sensor providing measurements within of \(\pm 1.0\)mm of the assigned comparative measurement method, VICON.

The validation indicated that a third, anti-drift sensor was not necessary in this application. However, it is noted that this was in a controlled laboratory environment, with extensive cleaning, monitoring and maintenance of equipment, operated by trained individuals. Outside of this environment, a more robust design including a ‘reset’ sensor may mitigate the influence of external factors on the data produced.

The reliability in which the sensor provides measurements will be assessed once the data processing methodology has been explained in Chapter 3.

2.3 Feedback display

The data output from the seat position sensor was fed into LabVIEW (National Instruments, Texas, USA) via a National Instruments NI9401 module (National Instruments, Texas, USA) and processed using a customised processing script in LabVIEW software, see Appendix C. This fed into ResROW, (Murphy et al., 2010), a program written for the acquisition of 3D kinematic data and kinetic data from an instrumented ergometer. Signals were synchronised with the other system using timed loops; each data input device being initiated by an individual loop, allowing for a loop to begin acquisition simultaneously and produce synchronised data. This process synchronises signal inputs into different receiver modules of the recording system, acquiring data from all motion and force sensors at 75Hz, writing data to an ASCII file, as shown in Table 3.3. Seat position was added to this as the 52nd data column. The instrumented ergometer system featuring a seat position sensor will now be referred as IES.
In addition to logging the data, a LabVIEW program displays real time feedback of seat position as part of a range of measurements. A data acquisition loop records the data provided from the 2 channels of the developed sensor, while another converts this into live position. This is displayed on screen in front of the athlete, Figure 2-5, with markers of minimal and maximal positions optionally available to allow individuals to observe the outcome of modifications to their technique. Seat velocity is calculated via equations of motion, and can be compared to handle velocity. This can, for example, indicate in real time if an athlete is significantly moving the handle before the seat, suggesting a documented sub-optimal aspect of rowing technique (Bull and McGregor, 2000), known as ‘tugging’ or ‘catching using the shoulders’. In Figure 2-5, on the top left is a display of the 4 FOB sensors, attached to the lumbar spine, pelvis, thigh and shin, which are green, yellow, red and blue respectively, combine to form a ‘stick-man’ representation of subject movement in the sagittal plane. The ergometer handle and seat are illustrated by the pink dot and rectangle respectively, with a further scale of seat position showing the range of travel.
A solution for recording the position of the seat of an indoor rowing ergometer was designed and validated. The solution uses optical sensors, with an accuracy of ±1.05mm, precision expressed by SD of 1.0. This measure was integrated into the instrumented ergometer introduced in Chapter 1. The next two chapters will discuss the methodology and protocol used to produce data from the IES, and data processing methods.
Chapter 3  Methodology

Chapter 1 and Chapter 2 introduced an instrumented ergometer and then documented the design and implementation of a new kinematic measurement, seat position to form the IES. The process of acquiring data for this study to meet the aims of Chapter 1 will now be discussed, including data acquisition, participants and protocol.

In the Introduction, 1.8.2 Instrumented ergometer outputs, Table 1.1 summarises the data ranges the IES measures, divided into three-dimensional data and non-three-dimensional data. Aside from the seat position sensor developed in Chapter 2, the equipment and signal acquisition of non-three dimensional measures for the handle, seat and foot-stretchers are not modified from that as described by Loh et al. (2004), Murphy (2009), Chee (2006) and Buckeridge (2012). The rationale and development of this equipment is described in their respective literature, and as such only the relevant or further developed methodology will be discussed in this work. Collective data acquisition of the IES will follow an outline of the methodology of capturing three dimensional kinematics for this study.

3.1 Recording three dimensional kinematics

The instrumented ergometer is shown in Figure 1-3. Three dimensional kinematics are captured using the FOB motion system. Translation (x, y, z) and rotation (α, β, γ) of the 4 receivers is quantified within the electromagnetic field of a transmitter. This is illustrated in Figure 3-1.
Figure 3-1: Plan view of instrumented ergometer and global axis systems. Inset illustration of 3D translation and rotations.

Table 3.1 describes the placement of the four FOB receivers with respect to the segment they represent in data recording, and the bony landmark relative to it. Figure 3-2 shows a subject using the instrumented ergometer with sensors in place, with the sensor number and the body segment it represents illustrated.
<table>
<thead>
<tr>
<th>Sensor</th>
<th>Placement</th>
<th>Body Segment</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Junction of 12th thoracic and 1st lumbar vertebral</td>
<td>Lumbar spine</td>
</tr>
<tr>
<td>S2</td>
<td>Junction of 5th lumbar and 1st sacral vertebral</td>
<td>Pelvis</td>
</tr>
<tr>
<td>S3</td>
<td>Lateral aspect of thigh</td>
<td>Thigh (Femur)</td>
</tr>
<tr>
<td>S4</td>
<td>Anterior aspect of shank</td>
<td>Shank (Tibia)</td>
</tr>
</tbody>
</table>

Table 3.1: Placement and body segment representation of the FOB receivers S1-S4

Figure 3-2: Placement and body segment representation of the FOB receivers S1-S4
3.2 Subject preparation and digitisation

Before a performance trial is undertaken, a subject must be prepared and digitised. S1 and S2 are affixed to a subject using adhesive pads (PALstickies™, PAL Technologies Ltd, Glasgow, Scotland). S4 is attached using a foam cuff and strapping. Before S3 is mounted to the subject, it is used as a stylus to record the position of body landmarks on the body in a digitisation process. Whilst the rower is seated on the ergometer seat a series of 10 non-performance recordings are made, where the stylus tip of S3 is placed on anatomical landmarks and rotated to create a cloud of 3D data. The relative offset of this cloud of 3D data is stored with respect to other sensors S1-3 already fixed to the subject, as listed in Table 3.2. S3 is then attached to the subject for biofeedback purposes.

<table>
<thead>
<tr>
<th>Digitised Anatomical landmark</th>
<th>Stored as offset from:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Posterior Superior Iliac Spine (RPSIS)</td>
<td>S2</td>
</tr>
<tr>
<td>Left Posterior Superior Iliac Spine (LPSIS)</td>
<td>S2</td>
</tr>
<tr>
<td>Right Anterior Superior Iliac Spine (RASIS)</td>
<td>S2</td>
</tr>
<tr>
<td>Left Anterior Superior Iliac Spine (LASIS)</td>
<td>S2</td>
</tr>
<tr>
<td>Lateral Femoral Epicondyle (LEPI)</td>
<td>S4</td>
</tr>
<tr>
<td>Medial Femoral Epicondyle (MEPI)</td>
<td>S4</td>
</tr>
<tr>
<td>Distal Apex of Lateral Malleolus (LMAL)</td>
<td>S4</td>
</tr>
<tr>
<td>Distal Apex of Medial Malleolus (MMAL)</td>
<td>S4</td>
</tr>
<tr>
<td>Dorsal Aspect of Fifth Metatarsal Head (MET5)</td>
<td>Laboratory space</td>
</tr>
<tr>
<td>Hip Joint Centre (HJC)</td>
<td>S2</td>
</tr>
</tbody>
</table>

Table 3.2: Digitised anatomical landmarks

3.3 Data Acquisition

Data from the FOB and load cells were acquired from separate data acquisition units, and software synchronised using a custom LabVIEW program as described in Chapter 1.8.1; the raw data output produced is shown in Table 3.3.
<table>
<thead>
<tr>
<th>Column number</th>
<th>Parameter</th>
<th>Column number</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Handle force</td>
<td>27</td>
<td>S3 y position</td>
</tr>
<tr>
<td>2</td>
<td>Chain length</td>
<td>28</td>
<td>S3 z position</td>
</tr>
<tr>
<td>3</td>
<td>Chain angle</td>
<td>29</td>
<td>S3 α angle</td>
</tr>
<tr>
<td>4</td>
<td>Stroke marker</td>
<td>30</td>
<td>S3 β angle</td>
</tr>
<tr>
<td>5</td>
<td>Front left seat force</td>
<td>31</td>
<td>S3 γ position</td>
</tr>
<tr>
<td>6</td>
<td>Front right seat force</td>
<td>32</td>
<td>S3 binary marker</td>
</tr>
<tr>
<td>7</td>
<td>Rear left seat force</td>
<td>33</td>
<td>S4 x position</td>
</tr>
<tr>
<td>8</td>
<td>Rear right seat force</td>
<td>34</td>
<td>S4 y position</td>
</tr>
<tr>
<td>9</td>
<td>ML seat coordinate</td>
<td>35</td>
<td>S4 z position</td>
</tr>
<tr>
<td>10</td>
<td>AP seat coordinate</td>
<td>36</td>
<td>S4 α angle</td>
</tr>
<tr>
<td>11</td>
<td>Seat force</td>
<td>37</td>
<td>S4 β angle</td>
</tr>
<tr>
<td>12</td>
<td>S1 x position</td>
<td>38</td>
<td>S4 γ position</td>
</tr>
<tr>
<td>13</td>
<td>S1 y position</td>
<td>39</td>
<td>S4 Binary marker</td>
</tr>
<tr>
<td>14</td>
<td>S1 z position</td>
<td>40</td>
<td>Time stamp (ms)</td>
</tr>
<tr>
<td>15</td>
<td>S1 α angle</td>
<td>41</td>
<td>Start position handle AP</td>
</tr>
<tr>
<td>16</td>
<td>S1 β angle</td>
<td>42</td>
<td>Start position handle IS</td>
</tr>
<tr>
<td>17</td>
<td>S1 γ angle</td>
<td>43</td>
<td>Handle coordinate AP</td>
</tr>
<tr>
<td>18</td>
<td>S1 binary marker</td>
<td>44</td>
<td>Handle coordinate IS</td>
</tr>
<tr>
<td>19</td>
<td>S2 x position</td>
<td>45</td>
<td>Foot force binary marker</td>
</tr>
<tr>
<td>20</td>
<td>S2 y position</td>
<td>46</td>
<td>RP vertical force</td>
</tr>
<tr>
<td>21</td>
<td>S2 z position</td>
<td>47</td>
<td>LP vertical force</td>
</tr>
<tr>
<td>22</td>
<td>S2 α angle</td>
<td>48</td>
<td>RP horizontal force</td>
</tr>
<tr>
<td>23</td>
<td>S2 β angle</td>
<td>49</td>
<td>LP horizontal force</td>
</tr>
<tr>
<td>24</td>
<td>S2 γ position</td>
<td>50</td>
<td>RP centre of pressure</td>
</tr>
<tr>
<td>25</td>
<td>S2 binary marker</td>
<td>51</td>
<td>LP centre of pressure</td>
</tr>
<tr>
<td>26</td>
<td>S3 x position</td>
<td>52</td>
<td>Seat position</td>
</tr>
</tbody>
</table>

NB: AP – Anterior-posterior, IS – superior-inferior, ML – medio-lateral, RP – Right foot plate, LP – Left foot plate

Table 3.3: Raw data outputs

### 3.4 Participants

Consideration must be made for the type of subjects to be used when producing data using the instrumentation and methods outlined previously. Less experienced athletes exhibit less refined muscle recruitment, with greater variance and variable levels of muscle co-activation when compared to more experienced athletes (Chapman et al., 2008). Therefore, it is essential to note the experience level of athletes when recording data. Elite athletes are ideal
as they exhibit consistent technique, as shown in statistical analysis by Murphy (2009). For this study, only elite athletes are tested.

When investigating relationships between variables, variance means sets of variables may not represent actual variance with respect to one another, and may just be a function of the variability of the sample considered. The identification of predictive relationships does not require a certain skill level or ability. However if the variance of samples assessed are not distributed randomly about the mean observed, then relationships, if any, will not possess the statistical significance to be confirmed or rejected. The skill level or success of the elite athletes to be tested does not affect their selection for this study, but their ability to consistently produce normally distributed variation of measured variables, and the inherent fitness and experience level of athlete athletes can reduce the effect of influential factors such as fatigue. However, it is an important part of experiment design to ensure that the equipment used is able to produce consistent measurements, and in data processing the variation of any set of measurements must be screened to confirm a normal distribution. This will be explained in further detail in 3.6.

As part of the funding for this project, GB Rowing Team athletes were tested using the equipment available at the MsK lab in Charing Cross Hospital. Real-time feedback, in addition to post-processed data, is provided to athletes and coaches. (The requirement for real-time feedback and the limited resources available to complete this study meant that motion capture systems such as VICON, which would provide the benefit of a greater number of simultaneous motion capture markers, was not suitable given the aforementioned constraints).

Ethics are in place for this and studies that use this equipment and similar protocols (ICREC_11_5_6 Kinetic and kinematic analysis of the lumbar spine and lower extremities during rowing). GB Rowing team athletes sign a ‘Letter of Commitment’, outlining the relationship between the GB Rowing team and its athletes, with athletes committing to undertake training, racing, and assessment methods at frequencies, times and locations as required by the GB Rowing Team management. This contract includes testing such as this study, and subjects in
this study were provided with an information sheet prior to the testing, were free to withdraw at any time, and ethics were in place for the protocol and testing methodology.

Athletes are categorized by gender and weight class. Weight class is lightweight or open weight (also referred to as heavyweight), where lightweight is less than 72kg and 59kg for males and females respectively. Lightweights may weigh up to 5kg more than this limit out of competition season.

3.5 Experimental Protocol

Data capture was performed in one testing session in April 2016 on 14 elite athletes (classified in this study as international representation in the sport of rowing) - all senior members of the Great Britain Rowing squad. Athletes were classified by class and gender as shown in Table 3.4.

<table>
<thead>
<tr>
<th></th>
<th>Open weight</th>
<th>Lightweight</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>1</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Female</td>
<td>6</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>All</td>
<td>7</td>
<td>7</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 3.4: Athlete numbers and classification

A protocol of subject testing was required to be a variation of typical rowing training or assessment as to not cause confusion or require acclimatisation, it needed to observe subjects at varying levels of intensity, without excessively fatiguing them as to influence their likelihood of participation or performing at incorrect intensities. An incremental step test of increasing intensity it is a familiar protocol for all competitive rowers, from beginner to elite and provides an opportunity to assess all levels of experience in the same manner. Athletes routinely perform such tests as part of their regular training (McGregor et al., 2005) to establish individual performance levels, and regular testing allows for longitudinal observations. This provides the opportunity to assess changes with respect to intensity whilst avoiding long continuous activity that may induce fatigue. It provides subjects with a test that is familiar and reasonable for the fitness and skill level of the subject.
In addition to kinematic and kinetic data, athlete weight was recorded.

The protocol used in these sessions has been completed by Great Britain Rowing Team athletes at Charing Cross Hospital since 2006, and follows a test protocol outlined in Table 3.5.

<table>
<thead>
<tr>
<th>Step</th>
<th>Duration</th>
<th>Stroke rate /min</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R18</td>
<td>3 minutes</td>
<td>18-20</td>
<td>Low Intensity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rest period, undefined, typically 2 minutes</td>
<td></td>
</tr>
<tr>
<td>R24</td>
<td>3 minutes</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rest period, undefined, typically 2 minutes</td>
<td></td>
</tr>
<tr>
<td>R28</td>
<td>3 minutes</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rest period, undefined, typically 2 minutes</td>
<td></td>
</tr>
<tr>
<td>RMAX</td>
<td>3 minutes</td>
<td>30+</td>
<td>High intensity - 'race pace'</td>
</tr>
</tbody>
</table>

Table 3.5: Test Protocol

Each performance trial of four three-minute steps was recorded as individual datasets for each minute of testing. Full trials would therefore produce 12 files of kinematic and kinetic measurements.

Of the trial performed in April 2016, 14 subjects participated. 4 subjects did not complete the full protocol. These 4 subjects did not complete the RMAX and/or R18 at the request of their coaches and/or physiologists, however it was noted this was not due to excess fatigue or current injuries. 4 open weight females (HWW), 4 lightweight males (LWM), 1 open weight male (HWM) and 1 lightweight female LWW completed all steps, Table 3.6. Any group comparisons from this point forward will only be made between HWW and LWW. The inclusion of the LWW and HWM data will also be considered.
Table 3.6: Participants and protocol completion. ‘x’ denotes a step that was not performed by subject due to external requirements from coaches/physiologists

<table>
<thead>
<tr>
<th>Athlete number</th>
<th>Steps completed (maximum of 4)</th>
<th>Athlete Class</th>
<th>R18</th>
<th>R24</th>
<th>R28</th>
<th>RMAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>4 HWW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>102</td>
<td>4 HWW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>103</td>
<td>3 HWW</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>104</td>
<td>3 HWW</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>105</td>
<td>4 LWM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>106</td>
<td>4 LWM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>107</td>
<td>4 LWM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>108</td>
<td>4 LWM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>109</td>
<td>4 LWW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>2 LWW</td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>111</td>
<td>2 LWW</td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>112</td>
<td>4 HWW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>113</td>
<td>4 HWW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>114</td>
<td>4 HWM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.6 Reliability Analysis

3.6.1 Methodology

Statistical analysis was used to assess the reliability of the seat measuring system, the data processing methodology and the consistency of the subjects being tested. The coefficient of multiple correlation (Kadaba et al., 1989) (also referred to as the coefficient of multiple determination (CMD) and coefficient of variance (CV) were calculated, processed and analysed by SPSS (version 23, IBM, New York, USA) and Microsoft Excel (Office 2016, Microsoft, Redmond, USA). Statistical significance was tested in a two-way ANOVA, with significance set for p<0.05 and Bonferroni post-hoc tests used to locate and confirm differences.

As this section aims to address the reliability of these averaged values, for each athlete, at each step intensity, the CMD and CV values will be calculated for 12 individual strokes within each step, for maximum and minimum seat position, in addition to the position at 15% into the stroke. The average position of maximum handle force for all the trials recorded in
this study was 14.9 (±2.5) and it was chosen as an exploratory selection for future investigation in addition to assessing reliability in statistical analysis as a potential replication of MHF position (the definition of the catch and the normalisation scale is based on handle force, so this was an exploratory selection for future analysis). The maximum and minimum scale refers to the laboratory co-ordinate system, where maximum and minimum correspond to positive and negative displacement in the Z axis.

CMD and CV was calculated between steps and between athlete classes where appropriate using group means and standard deviations.

3.6.2 Results for Reliability analysis

CMD values are listed in Table 3.7. Mean calculated CMD was 0.97±0.02 for maximum values, 0.98±0.02 for minimum values. No significant differences were detected across stroke rates, or between athlete groups. The CMD and therefore consistency of identification of the 15% point is lower than of the points of inflection, limiting the application of this timing point as a consistent point of reference. The 15 % position is determined in reference to the catch position, defined as previously discussed through algorithms using values of handle force. The identification of seat position at 15% of the stroke is subject to variance in the identification of handle force, and the normalisation of the stroke about the onset of handle force, this may explain the calculated values of CMD.
<table>
<thead>
<tr>
<th>Step</th>
<th>Seat Position Maximum</th>
<th>Seat Position Minimum</th>
<th>Seat Position at 15%</th>
</tr>
</thead>
<tbody>
<tr>
<td>R18</td>
<td>0.99 ±0.01</td>
<td>0.99 ±0.01</td>
<td>0.94 ±0.02</td>
</tr>
<tr>
<td>R24</td>
<td>0.98 ±0.01</td>
<td>0.98 ±0.02</td>
<td>0.91 ±0.03</td>
</tr>
<tr>
<td>R28</td>
<td>0.98 ±0.01</td>
<td>0.99 ±0.01</td>
<td>0.91 ±0.02</td>
</tr>
<tr>
<td>RMAX</td>
<td>0.95 ±0.04</td>
<td>0.97 ±0.05</td>
<td>0.91 ±0.02</td>
</tr>
<tr>
<td>Average</td>
<td>0.97 ±0.02</td>
<td>0.98 ±0.02</td>
<td>0.92 ±0.03</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Group</th>
<th>Step</th>
<th>Seat Position Maximum</th>
<th>Seat Position Minimum</th>
<th>Seat Position at 15%</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWW</td>
<td>R18</td>
<td>0.98 ±0.01</td>
<td>0.99 ±0.02</td>
<td>0.94 ±0.02</td>
</tr>
<tr>
<td></td>
<td>R24</td>
<td>0.98 ±0.01</td>
<td>0.98 ±0.01</td>
<td>0.90 ±0.05</td>
</tr>
<tr>
<td></td>
<td>R28</td>
<td>0.98 ±0.01</td>
<td>0.99 ±0.01</td>
<td>0.91 ±0.02</td>
</tr>
<tr>
<td></td>
<td>RMAX</td>
<td>0.93 ±0.07</td>
<td>0.95 ±0.08</td>
<td>0.91 ±0.01</td>
</tr>
<tr>
<td>LWM</td>
<td>R18</td>
<td>0.99 ±0.01</td>
<td>0.99 ±0.01</td>
<td>0.94 ±0.03</td>
</tr>
<tr>
<td></td>
<td>R24</td>
<td>0.99 ±0.01</td>
<td>0.99 ±0.01</td>
<td>0.91 ±0.01</td>
</tr>
<tr>
<td></td>
<td>R28</td>
<td>0.98 ±0.01</td>
<td>0.99 ±0.01</td>
<td>0.90 ±0.03</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>0.97 ±0.01</td>
<td>0.99 ±0.01</td>
<td>0.90 ±0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.97 ±0.02</td>
<td>0.98 ±0.02</td>
<td>0.92 ±0.03</td>
</tr>
</tbody>
</table>

Table 3.7: Coefficients of multiple determination (CMD)

CMD for seat position maximum, minimum and value at 15% of stroke. Values for all subjects, and then compared between HWW and LWW.

CV demonstrated in Table 3.8. In the first stage, analysis 1, it was observed that the standard deviation significantly increased with step. Exploration of the data found that one individual athlete was both inconsistent and unreliable, i.e. measurements were variable with no relationship to time, intensity or other known variables. This was shown in their seat position data and other kinematic measurements. High levels of variance both within and between intensity steps, as exhibited by this subject, is why elite athletes were chosen for this study, i.e. to avoid such variance. Therefore due to the inconsistency and unreliability of this subject, this data was excluded from further analysis of the reliability of seat position measurement. The corresponding data set was adjusted and the calculations repeated to produce CV values ‘b’.
<table>
<thead>
<tr>
<th>Step</th>
<th>Seat Position Maximum</th>
<th>Seat Position Minimum</th>
<th>Seat Position at 15%</th>
</tr>
</thead>
<tbody>
<tr>
<td>R18</td>
<td>1.5 ±1.4</td>
<td>6.2 ±0.5</td>
<td>3.8 ±1.9</td>
</tr>
<tr>
<td>a R24</td>
<td>2.3 ±1.7</td>
<td>1.1 ±1</td>
<td>7.3 ±3.1</td>
</tr>
<tr>
<td>R28</td>
<td>3.4 ±3</td>
<td>0.7 ±0.6</td>
<td>7.6 ±3.8</td>
</tr>
<tr>
<td>RMAX</td>
<td>6.3 ±5.2</td>
<td>2.0 ±3.7</td>
<td>9.0 ±5.5</td>
</tr>
<tr>
<td></td>
<td>3.3 ±2.8</td>
<td>2.5 ±1.4</td>
<td>6.9 ±3.6</td>
</tr>
</tbody>
</table>

Table 3.8: Coefficients of variance
(average % ±SD) for seat position maximum, minimum and value at 15% of stroke. “a” included all subjects, “b” removed 1 subject deemed to be an excessively inconsistent.

Maximum values of CV were observed at RMAX for Seat Position Maximum and Minimum, with significantly higher variance and standard deviation of this variance. The seat position maximum, the most anterior position of the seat during the rowing cycle which occurs near the end of the recovery and the start of the drive is subject to significantly more variance at higher rates than the minimum position (at the end of the drive phase). Variation between LWW and HWW is shown in Table 3.9.

<table>
<thead>
<tr>
<th>Step</th>
<th>Seat Position Maximum</th>
<th>Seat Position Minimum</th>
<th>Seat Position at 15%</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R18</td>
<td>2.4 ±1.8</td>
<td>0.6 ±0.7</td>
<td>3.0 ±1.8</td>
</tr>
<tr>
<td>R24</td>
<td>3.0 ±1.5</td>
<td>1.3 ±0.6</td>
<td>7.9 ±4.9</td>
</tr>
<tr>
<td>R28</td>
<td>2.6 ±1.1</td>
<td>0.9 ±0.8</td>
<td>6.7 ±2.9</td>
</tr>
<tr>
<td>RMAX</td>
<td>6.0 ±4.3</td>
<td>3.6 ±6</td>
<td>10.5 ±6.8</td>
</tr>
<tr>
<td>LWM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R18</td>
<td>0.9 ±0.7</td>
<td>0.5 ±0.2</td>
<td>4.4 ±2.5</td>
</tr>
<tr>
<td>R24</td>
<td>1.2 ±0.4</td>
<td>0.4 ±0.2</td>
<td>7.1 ±1.2</td>
</tr>
<tr>
<td>R28</td>
<td>2.3 ±1.4</td>
<td>0.6 ±0.4</td>
<td>8.7 ±4.7</td>
</tr>
<tr>
<td>RMAX</td>
<td>6.5 ±7.1</td>
<td>0.7 ±0.4</td>
<td>8.8 ±5.6</td>
</tr>
</tbody>
</table>

Table 3.9: Coefficients of variance (average % ±SD) for seat position maximum, minimum and value at 15% of stroke

HWW and LWM do not exhibit significant differences for seat position maximum values between rates or between groups.
The results of this reliability analysis has demonstrated the seat position sensor to identify position of seat position consistently for individual athletes, between intensities of effort and between athlete groups. Values of CV did not change between rates to be identified as statistically significant, but the standard deviation of these measures of variance did significantly increase with step. This suggests a variation in technique being performed by some subjects as the step test was carried out, or less of an ability to maintain consistency.

3.7 Conclusion

The methodology to produce data from performance trials has been outlined, and the athlete group and protocol explained. The seat position sensor was demonstrated to reliably identify position of seat for the subject group and protocol used in this study. As such the accuracy and reliability of the seat position sensor has been established.

The methods by which the data was processed into that suitable for analysis is described in the following chapter.
Chapter 4 Data Processing

Data is processed in three steps:

- calculating three dimensional kinematics;
- normalising the processed outputs; and
- extraction of data to be assessed.

These are completed in LabVIEW, Matlab (Mathworks, Natick, Massachusetts, USA) and Matlab, respectively.

4.1 Acquiring and treating data

Kinematic data is defined by the co-ordinate system it refers to - global or local. The global or laboratory system is in reference to the area in which measurements are made, and can be assumed to be fixed in this example. Local coordinate systems are fixed relative to objects free to translate and rotate. In the case of an individual sensor interacting with a subject or target object, the outputs are relative to the sensor and the subject, not the global, fixed, co-ordinate system. Local co-ordinates can be processed and converted to global coordinates.

A three dimensional kinematic model for a unilateral lower limb, lumbar spine and pelvis was developed by Chee (2006). This model was written in LabVIEW by Murphy (2009) using the Grood and Suntay (1983) joint co-ordinate system (JCS) methodology to process 3D joint kinematics. This JCS method and model remains the same for the study that forms this thesis, integrated into a LabVIEW program for kinematic processing of captured data (calc3Dking.exe).

The LabVIEW program (calc3Dking.exe) first uses the non-performance digitation recordings to calculate the local offsets of each bony landmark from its relevant sensor by applying offsets by the relationships listed in Table 3.2. When the recorded offsets are applied to FOB sensor positions and rotations, the 3D positions of the ten points recorded in the digitisation recording process are calculated in the global co-ordinate system. The kinematic model defines five joints. The lumbar-pelvic (L5/S1) is tracked offset from S2, the right knee (KJC), right ankle (AJC) and foot (FJC) joints are derived from the digitised landmarks, and the FOB tibia receiver. The right hip (HJC) is identified during the non-
performance recordings listed in Table 3.2, by attaching S3 to the thigh of the subject and whilst standing the subject rotates the leg about the hip joint through a full range of motion. A sphere fitting procedure (Gamage and Lasenby, 2002) is used to find the centre of this rotation and therefore the HJC. The vectors between the digitised landmarks define five body segments with individual local co-ordinates, representing the lumbar, pelvis, femur, tibia and foot. FJC refers to the head of the 5th metatarsal, which is assumed to be fixed to the footplate of the ergometer due to the strapping of the feet. Data from performance trials is then applied using JCS method and these defined joint centres and segments to produce an output of data listed in Table 4.1. A detailed description of the local co-ordinate systems is given by Murphy (2009)\(^1\). Three dimensional kinematic variables are not changed from the raw output listed in Table 4.1, however seat position and foot forces have been added.

With respect to clinical descriptions, positive and negative α angles refer to extension and flexion respectively. Pelvic tilt represents the sagittal angle of the pelvis in the global coordinate system, where a vertical orientation would be 0°, where anterior and posterior rotations are positive and negative respectively.

\(^1\) Pg. 73-79, Chapter 4.3 *Coordinate systems*
<table>
<thead>
<tr>
<th>Column number</th>
<th>Parameter</th>
<th>Column number</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Handle force</td>
<td>27</td>
<td>L5S1 α angle</td>
</tr>
<tr>
<td>2</td>
<td>Front left seat force</td>
<td>28</td>
<td>L5S1 β angle</td>
</tr>
<tr>
<td>3</td>
<td>Front right seat force</td>
<td>29</td>
<td>L5S1 γ angle</td>
</tr>
<tr>
<td>4</td>
<td>Rear left seat force</td>
<td>30</td>
<td>HJC α angle</td>
</tr>
<tr>
<td>5</td>
<td>Rear right seat force</td>
<td>31</td>
<td>HJC β angle</td>
</tr>
<tr>
<td>6</td>
<td>ML seat coordinate (COP)</td>
<td>32</td>
<td>HJC γ angle</td>
</tr>
<tr>
<td>7</td>
<td>AP seat coordinate (COP)</td>
<td>33</td>
<td>KJC α angle</td>
</tr>
<tr>
<td>8</td>
<td>Seat force</td>
<td>34</td>
<td>KJC β angle</td>
</tr>
<tr>
<td>9</td>
<td>S1 α angle</td>
<td>35</td>
<td>KJC γ angle</td>
</tr>
<tr>
<td>10</td>
<td>S2 α angle</td>
<td>36</td>
<td>AJC α angle</td>
</tr>
<tr>
<td>11</td>
<td>Body mass</td>
<td>37</td>
<td>AJC β angle</td>
</tr>
<tr>
<td>12</td>
<td>L5S1 X</td>
<td>38</td>
<td>AJC γ angle</td>
</tr>
<tr>
<td>13</td>
<td>L5S1 Y</td>
<td>39</td>
<td>FJC α angle</td>
</tr>
<tr>
<td>14</td>
<td>L5S1 Z</td>
<td>40</td>
<td>Time stamp (ms)</td>
</tr>
<tr>
<td>15</td>
<td>HJC X</td>
<td>41</td>
<td>FJC offset</td>
</tr>
<tr>
<td>16</td>
<td>HJC Y</td>
<td>42</td>
<td>Ankle Joint width</td>
</tr>
<tr>
<td>17</td>
<td>HJC Z</td>
<td>43</td>
<td>Handle position AP</td>
</tr>
<tr>
<td>18</td>
<td>KJC X</td>
<td>44</td>
<td>Pelvic tilt</td>
</tr>
<tr>
<td>19</td>
<td>KJC Y</td>
<td>45</td>
<td>Foot force binary marker</td>
</tr>
<tr>
<td>20</td>
<td>KJC Z</td>
<td>46</td>
<td>RP vertical force</td>
</tr>
<tr>
<td>21</td>
<td>AJC X</td>
<td>47</td>
<td>LP vertical force</td>
</tr>
<tr>
<td>22</td>
<td>AJC Y</td>
<td>48</td>
<td>RP horizontal force</td>
</tr>
<tr>
<td>23</td>
<td>AJC Z</td>
<td>49</td>
<td>LP horizontal force</td>
</tr>
<tr>
<td>24</td>
<td>FJC X</td>
<td>50</td>
<td>RP Centre of pressure</td>
</tr>
<tr>
<td>25</td>
<td>FJC Y</td>
<td>51</td>
<td>LP Centre of pressure</td>
</tr>
<tr>
<td>26</td>
<td>FJC Z</td>
<td>52</td>
<td>Seat position</td>
</tr>
</tbody>
</table>

NB: AP – Anterior-posterior, IS – superior-inferior, ML – medio-lateral, RP – Right foot plate, LP – Left foot plate

Table 4.1: Processed data outputs of IES

4.1.1 Data normalisation

All the data in Table 4.1 was normalised over a cycle based on handle force. The onset of handle force has been identified as a reliable and repeatable method of identifying the catch position (Holt et al., 2003). A normalised rowing stroke is represented as 101 data points from 0 – 100 %. The \( n^{th} \) stroke begins at the \( n^{th} \) catch, through the drive and recovery phase until the \( n+1^{th} \) catch. The catch position is identified by applying a six condition algorithm to
handle force measurements, as documented by Murphy (2009). The algorithm scans through
the data until it locates four sequential data points that satisfied six conditions; the first and
fourth value must be above and below relevant thresholds (these total four of the six
conditions), a defined relationship must exist between the magnitudes of the four values, and
that the next catch cannot occur within ten rows of the current catch position. A MATLAB
script applies these algorithms to define the catch positions, before chronologically moving
the rows of data from the \( n \)th catch to the \( n+1 \)th catch and place them in array \( n \). Linear
interpolation transforms the data of Table 4.1 into 101 rows. All arrays are then placed in
chronological order and then saved as a normalised data output. An additional column is
saved - % of stroke, to produce a 53 column dataset.

4.1.2 Data extraction, reduction & processing

A data extraction program was created in MATLAB
\((\text{Extract\_Mean\_Stroke\_and\_calculations.exe})\) to output data suitable for statistical analysis,
and completed three processes.

For each normalised step, the first three and last three strokes were deleted to account for any
acceleration or deceleration at the start of finish of each step. The remaining strokes within
each step were then averaged to produce a single mean stroke. For each subject, each minute
step of the 12-minute protocol performed would now be represented by a mean stroke, with
101 rows 0 - 100 % of the stroke,

Non-sagittal kinematic variables were excluded from the data in this process. Previous
research has demonstrated these variables to be of low influence on technique, with 0.53% of
all non-sagittal rotations changing significantly longitudinally or with intensity of effort
(Murphy, 2009). It is also not proposed that medio-lateral translations or rotations will be
able to be predicted by seat and handle measurements which are constrained to translations in
the sagittal plane. Finally, as considered by Buckeridge et al. (2012) such out of plane
rotations would be difficult to observe or implement by athletes.
The program also extracted new parameters, and added these to the kinematic and kinetic list listed previously in Table 4.1, and produces the list of outputs in Table 4.2.

The script calculated the timing point within the stroke for the following discrete points, and these were used as references for other variables to be extracted at these discrete points for each subject:

- Catch % – start of stroke (defined by the onset of handle force as described in section 4.1.1), occurs at 0%,
- MHF % - timing of peak handle force,
- Finish % – defined with the same parameters as the catch, but to identify the timing of end of the application of handle force,
- Handle Inflection Front % - timing of the most anterior position of the ergometer handle (highest in Z direction) at the onset of posterior travel (to avoid erroneous timing measures if the handle remains stationary),
- Handle Inflection Finish % - timing of the most posterior position of the ergometer handle (minimum in Z direction) at the onset of anterior travel (to avoid erroneous timing measures if the handle remains stationary).
- Seat Inflection Front % (SIF) - timing of the most anterior position of the ergometer seat (highest in Z direction) at the onset of posterior travel (to avoid erroneous timing measures if the seat remains stationary),

Variables or calculations not previously introduced are as follows:

- $\Delta LSJ\alpha$ catch to MHF – the change in the angle L5/S1 $\alpha$ from the catch position to MHF. $\Delta LSJ\alpha$ has been demonstrated by (Murphy, 2009) to act as a pertinent predictor of performance,
- $\Delta LSJ\alpha$ catch to finish – as above to the finish timing point,
- $\Delta LSJ\alpha$ Handle Inflection to Catch – L5/S1 $\alpha$ from timing of handle inflection front to the timing of the catch,
- MHF/Body Mass – total max handle force normalised by subject body mass
- Resultant Foot Force at MHF/Body Mass – Measures of Total Resultant Foot Force at the timing of MHF, normalised by subject body mass.
• Sum Foot Forces from catch – MHF – Introduced by (Buckeridge et al., 2012), the cumulative total foot force applied from the timing of the catch to MHF.

• Catch Timing Score – A new measure, to define the relative timing of handle and seat. Calculated as the difference in the timing of SIF and Handle Inflection Front\(^2\),

• Leg Trunk Ratio (LTR). A new measure\(^3\) to define the displacement of the handle and seat relative to their own minimal anterior positions,

• Power Output - subject power output, calculated using the integral of the handle force and the time it was applied (note that % of stroke was converted into time based on the stroke rate for each unique step, not the suggested rate of the test protocol),

• Min seat force / body weight – a performance parameter used and define by (Buckeridge et al., 2012), a parameter calculated to define the force applied to the seat at the finish position, the higher the ratio, the more vertical force applied, which is suggested to negatively influence on-water rowing performance,

• Suspension 1 – the cumulative force applied to the seat, divided by body mass from the catch to MHF. Suspension represents the amount of force the athlete has taken off the seat during the drive of the rowing stroke. This is achieved by effectively transferring force from the feet to the handle, and thus the force applied to the seat decreases. Suspension 1 represents just the first portion of the drive, up to the timing of MHF and was implemented by (Murphy, 2009),

• Suspension 2 – the cumulative force applied to the seat, divided by body mass, from the catch to the finish timing points. As for Suspension 1, but for the whole of the drive phase,

The script calculated the changes in parameters between these discrete points, before saving a collated dataset describing each athlete at the selected discrete points. Definitions of variables or calculations not previously introduced are described in Table 4.2.

---

\(^2\) In the timeline of this study, KLESHNEV, V. 2015. Catch Indicators. Rowing Biomechanics Newsletter No 174, ibid. discussed the application of on-water rowing biomechanics system, with measures for a ‘Catch Timing Factor’ and ‘Leg Trunk Factor’. This was published after these concepts were identified during this study, during which the concepts of CatchTimingScore or Leg Trunk Ratio were not made public or published. The author of this study acknowledges the existence of Kleshnev’s work, however the application is distinct from this study, is defined using different methods and is not considered in reference to 3D kinematics.

\(^3\) As Above.
### Descriptive Non-3D Kinematics

<table>
<thead>
<tr>
<th>Subject Identifier</th>
<th>Seat Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>Handle Position</td>
</tr>
<tr>
<td>Class</td>
<td>COP Anterior-posterior</td>
</tr>
</tbody>
</table>

#### Stroke Profile

- MHF %
- Handle Inflection Front %
- Handle Inflection Finish %
- Knee Up Occurs Recovery %
- Catch % (always 0%)*
- Seat Inflection Front %

#### 3D Kinematics

- LSJ Z
- LSJ α
- HJC Z
- HJC α
- Pelvic Tilt
- KJC Z
- KJC α

#### Extracted parameter for 3D kinematics

- ΔLSJ α catch to MHF
- ΔLSJ α catch to finish
- ΔLSJ α Handle Inflection to Catch

#### Extracted Parameter for Non-3D kinematics

- Δseat'
- Δhandle'
- ΔCOP'
- MHF/Body Mass
- Resultant Foot Force at MHF/Body Mass
- Power Output
- Minimum seat force / body weight
- Suspension 1
- Suspension 2
- Handle Force Slope
- Leg Trunk Ratio (LTR)

---

Table 4.2. Addition parameters calculated in data extraction program

*Italics identify these points to be captured at every ‘Stroke Profile’ point. * identify constant stroke profile points not recorded, but which are used for those measurements in italics. ‘’ identifies parameters that are extracted using combinations of two of the stroke profile % points, eg Δseat Catch – MHF represents the change in seat position from the catch timing point to the time at which maximum handle force is recorded.

---

The outputs were saved to individual files for each minute of recording the four intensity steps, to produce 12 files, 3 for each of the intensity steps.
4.2 Statistical methodology

4.2.1 Rationale

Having met an aim of this thesis, developing addition kinematic measurement of an indoor rowing ergometer and integrating it into a system to capture a range of kinetic and kinematic data of the rowing stroke, the next aim is to investigate the relationship between kinematic measures such as the seat position and known performance related 3D kinematics.

As described in Chapter 1, Proposed Outcomes, it is hypothesised that the movement of the seat, handle, and the forces at these points will be able to indicate the sequencing and description of the movement of the athlete, known in some variations to be favourable for maximising performance outputs. Using past literature and research, as well as the performance outputs measured in this study, known influencers of performance can be selected, and compared to the non-three dimensional kinematic measurements made. When multiple measurements are available, variation in performance outputs can be compared to variations in other measurements. Comparing two variables can give insight into variation, such as variation with intensity of effort, between groups, etc., but the influence of multiple variables on these performance outputs can give greater insight into underlying relationships. With sufficient data sets, and a comprehensive analysis, one or more variables may be found to predict variations in another parameter, with a calculated degree of certainty. If sufficiently accurate, and sufficiently validated and rigorously tested for validity, such relationships can be used to provide predictions for measurements otherwise not available, but are now possible to predict, with an estimated level of certainty and margin of error.

4.2.2 Methodology

The predictive relationship between variables were assessed with regression modelling using SPSS (version 23, IBM, New York, USA). Multiple regression modelling was used to generate model(s) of a dependent variable based on multiple selected independent variables.

The quality of a regression model can be assessed on the $R^2$ and adjusted $R^2$ scores of the model. The difference between an observed dependent variable and the predicted variable
using the corresponding independent variable is known as the residual. The fit of a regression model to account for the variance in the variables observed creates the R\(^2\), while an adjusted score considers the variance in the dependent variable based on the number and variance of the independent variables, and allows for comparison between models with different independent variables. R\(^2\) ranges from 0 to 1, where 1 represents a perfect explanation of the relationship between variables, and 0 indicates no relationship. However, for the R\(^2\) values and the regression model to be valid the variables input, the properties of the model and the residuals must be assessed, if they do not satisfy the assumptions of the regression method, or properties exceed problematic levels the model must be rejected or modified and reassessed.

In this study, linear modelling will be used as an initial assessment of variables suggested normal distribution of data, and as non-linear models are not possible to score in the same way as linear models, have not be used.

Linear models must be tested for the following to be valid:

i. Normality of residuals. The distribution of errors (residuals) produced by a regression model should be randomly distributed about a mean of zero. This can be assessed by viewing a histogram of residuals.

ii. Normality of Data. Independent and dependent variables should be normally distributed, but this is not as important as normality of residuals.

iii. Auto-correlation. Residuals of the different observations should not be correlated. The residuals of a regression analysis can be tested for auto-correlation with a Durbin-Watson test, scoring from 0-4, where no autocorrelation scores 2.

iv. Homoscedasticity. For each case of corresponding observations, the variance should be constant. A scatter plot of residuals against dependent variable is used to assess this, and the observation of a funnel shape indicates homoscedasticity.

v. Multicollinearity. High correlation between two predictors within a regression model can be problematic, the variance influence factor (VIF), where scores exceed 8, suggest multicollinearity between independent variables may be influencing the model.

vi. Influence of individual cases. The accuracy of a regression model with respect to the data set input is dependent upon the cases input. The model may be influenced by a
small number of cases, compromising the model as it attempts to satisfy all input datasets. Data must first be screened before the model is created for outliers of extreme variance that may be influenced by measurement, recording or data processing error. During regression modelling, any individual cases with standardised residuals greater than 3.0 will be excluded as an outlier, but noted in each case. Statistics of maximum Cook’s distance (<1.0), maximum Mahalanobis distance and mean leverage of individual cases will be observed. High leverage and Mahalonobis indicates individual influence on the model.

vii. Significance. In addition to the quality of fit described by the adjusted $R^2$ score, the independent variables must satisfy their inclusion through tests for significance. F-test statistics will require effects to exhibit p-values <0.05 in the final model.

The processed and reduced data set in Table 4.2, was subjected to these criteria before, during and after its inclusion in multiple linear regression modelling, performed in SPSS (version 23, IBM, New York, USA). Independent variables were selected for each dependent variable through a combination of the Best Subsets method, where all potential individual variables and all potential combinations are considered and included and removed based on F-statistics, excluding effects with p-values less than 0.05. The resultant model is then repeated using the enter method of multiple linear regression modelling to test the model meets the criteria listed above. The model is then rejected or modified and tested again until it is either rejected or meets the required criteria.
Chapter 5  Results

The results from this study will be presented in 3 parts:

1. Descriptive results of novel measurements and calculated variables. These are presented to stand alone in describing the motion of the ergometer seat, meeting an objective of this study to provide measurement of seat position during ergometer rowing. Handle measurements, and relative timing and movement of the seat and handle are then described, ahead of their inclusion in latter analysis.

2. Regression analysis
   – Having introduced the methodology in Chapter 4.2, the independent and dependent variables are defined.
   – Descriptive statistics are shown for the variables used in the regression analysis.
   – The output of the regression modelling is demonstrated, with one example of the statistical analysis process used described and shown in full, with the remaining summarised, but shown in the same level of detail as the example in Appendix D – Results of Regression Analysis.

3. The regression modelling outputs are summarised to conclude the chapter, ahead of the discussion of the results in the following chapter.

5.1 Descriptive Results

5.1.1 Descriptive Results of Seat

Figure 5-1 shows the average travel of the ergometer seat during this study between intensity steps. Recall that the data processing, Chapter 4, normalises data about the onset of handle force, where the catch is 0%. Referring to the diagram of the rowing stroke shown in Figure 1-1, 0% is the catch, where the legs push against the footstretcher, applying force through the body to the handle. The seat and handle move in a posterior direction during the drive phase, from 0-30%. As the knee joint fully extends, the stroke is finished with the flexion of the arms, to the finish position in the range 30-40%. The recovery phase now begins, initiated.
with extension of the arms, and flexion of the hip before knee joint flexion brings the athlete into the catch position once again at around 90%.

Figure 5-1: Average Seat Position Data. SIF, SI1, SI2 denote points of inflection, i.e. direction change, at three points in the stroke

Three inflection points can be observed, a maximum, and two minimal inflection locations. The maximum will hereby be known as seat inflection front (SIF), seat inflection 1 (SI1) and Seat Inflection 2 (SI2).

It is notable that the change of direction of the seat, SIF, occurs before the ‘catch’ position, i.e. the application of handle force at all intensities. After the drive phase, it can be seen that the seat comes to a stop, SI1, travels in an anterior direction, changes direction once again before a final inflection to anterior travel at SI2. The timing of these three inflection points, SIF, SI1 and SI2, are plotted in Figure 5-2.
Of the three timing points of seat inflection, plotted by distribution in Figure 5-2, only % Seat Inflection Front changes significantly between RMAX and R18, and RMAX and R28. This demonstrates a change in technique between rate steps for this variable, with the seat inflection occurring a mean of 4% earlier in the stroke cycle.

As described in Chapter 3, the 100 and 0% points of the stroke are defined as the catch, where the handle force profile meets a set of reliable and predefined set of criteria, and therefore the handle must also change direction before seat. The influence of this timing gap between the inflection of the seat, the handle and 3D kinematic inflections are worthy of further study.
Figure 5-2: Seat Inflection point as % of stroke for step

The boxes represent the 2\textsuperscript{nd} and 3\textsuperscript{rd} quartiles for that variable, upper and lower ticks are the lower and upper quartiles. Changes between steps is illustrated by a line through each mean value.
Figure 5-3 compares seat position between LWM and HWW. SIF, SI1 and SI2 for LWM is more anterior than HWW, this may be explained by the sample of HWW being of greater height or limb lengths than LWM. HWW exhibited greater variation within and between intensity steps.

Figure 5-3: Seat position with respect to step for LWM and HWW
Scales and legend are identical, displacement on Y axis, in mm ± standard deviation, % of stroke on X axis.
5.1.2 Other relevant/novel descriptive results

5.1.2.1 Handle timing

The timing of the inflection of the handle is illustrated in Figure 5-4. Timing of the handle inflections shows statistically significant differences between R18 and RMAX for both Handle Inflection Back (i.e. finish of the stroke) and the timing of MHF.

Figure 5-4: Handle timing with respect to intensity step
5.1.2.2 **Combining Seat and Handle timing – Catch Timing Score**

The timing of the inflections of the seat and handle, Figure 5-2 & Figure 5-4 demonstrated significant variation of timing between low and high intensity steps for the seat around the catch position, but less variation of the handle change of direction. To investigate the potential causes and consequence of changes in timing of these two kinematic measurements, the timing of the handle and seat can be combined to form Catch Timing Score, Figure 5-5, defined by the timing difference between the catch timing of the seat and handle. The timing of the seat is shown to vary proportionately more than the handle.

---

**Figure 5-5: Timing of Handle and seat inflection with derived parameter Catch Timing Score**
5.1.2.3 Combining Seat and Handle movements – Leg Trunk Ratio

The relative travel of the seat and handle is described by the Leg Trunk Ratio, which is the ratio of seat travel to handle travel, and was calculated at the Catch, MHF and Finish, Figure 5-6. The LTR shows very low variation at the finish, more so at MHF and again more variable, with a greater spread of value at the catch.

---

**Figure 5-6: Leg Trunk Ratios between steps**
5.2 Regression analysis

5.2.1 Input Independent Variables

The non-3D-kinematic variables listed in Table 4.2, are used as independent variables, with the stroke timing points of SI1 and SI2 added to form Table 5.1.

<table>
<thead>
<tr>
<th>Independent Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
</tr>
<tr>
<td>Class</td>
</tr>
<tr>
<td>Step</td>
</tr>
<tr>
<td>Mass</td>
</tr>
<tr>
<td>MHF %</td>
</tr>
<tr>
<td>Finish %</td>
</tr>
<tr>
<td>Handle Inflection Front %</td>
</tr>
<tr>
<td>Handle Inflection Occurs</td>
</tr>
<tr>
<td>Finish %</td>
</tr>
<tr>
<td>Knee Up Occurs Recovery %</td>
</tr>
<tr>
<td>Catch % (always 0%)*</td>
</tr>
<tr>
<td>Seat Inflection Front %</td>
</tr>
<tr>
<td>Seat Inflection 1 %</td>
</tr>
<tr>
<td>Seat Inflection 2 %</td>
</tr>
<tr>
<td>Seat Position</td>
</tr>
<tr>
<td>Handle Position</td>
</tr>
<tr>
<td>COP Anterior-posterior</td>
</tr>
<tr>
<td>MHF/Body Mass</td>
</tr>
<tr>
<td>Δseat§</td>
</tr>
<tr>
<td>ΔCOP§ AP</td>
</tr>
<tr>
<td>Δhandle§</td>
</tr>
<tr>
<td>Catch Timing Score</td>
</tr>
<tr>
<td>Power Output</td>
</tr>
<tr>
<td>Leg Trunk Ratio (LTR)</td>
</tr>
<tr>
<td>Handle Force Slope</td>
</tr>
</tbody>
</table>

Table 5.1: Independent variable list for regression analysis

*italics identify these points to be captured at every 'Stroke Profile' point. * identify constant stroke profile points not recorded, but which are used for those measurements in italics. § identifies parameters that are extracted using combinations of two of the stroke profile % points, eg Δseat Catch – MHF represents the change in seat position from the catch timing point to the time at which maximum handle force is recorded.
5.2.2 Dependent Variables

The dependent variables were selected as those demonstrated and established in literature (as discussed in Chapter 1 to be predictors or relevant to rowing performance (Murphy, 2009). If the independent variables are able to predict the dependent variables listed here, then non-three dimensional kinematics will be able to be used to estimate these known performance related parameters in contexts where direct measurement is not feasible.

1) ΔLSJ $\alpha$ catch to MHF. Minimising the change in the angle in L5/S1 associated with performance outputs in ergometer rowing.
2) Catch LSJ $\alpha$. Selected to investigate the influence of non-3D variables on the position of the athlete at the catch position.
3) MHF LSJ $\alpha$. Selected to investigate the influence of non-3D variables on the position of the athlete at MHF.
4) Finish LSJ $\alpha$. Increased lumbar extension improved performance parameters.
5) Catch LSJ Z. A more posterior position of the LSJ was associated with a later timing of the finish of the stroke and higher power output.
6) MHF LSJ Z. A more anterior position of the LSJ at this point was associated with a later timing of the finish of the stroke, higher stroke length and suspension achieved.
7) Finish LSJ Z. Selected to investigate the influence of non-3D variables on the position of the athlete at finish.
8) Knee up LSJ Z. More anterior position beneficial.
9) Suspension 1. A higher value is beneficial for power output as earlier suspension indicates a more effective translation of power from the handle to feet.
10) Suspension 2. As above, but totalled over the entire drive of the rowing stroke.
11) Min seat force/BW. A lower overall ratio indicates a reduced downward force on the seat at the finish, suggested to be deleterious to on-water rowing performance.
12) Knee up Recovery %. Timing the rising of the knees later in the stroke is suggested to be beneficial as there is a greater period of time after the finish of the stroke for anterior rotation of the pelvis.
13) PelvisΔ SIF to catch. This study wished to investigate the influence of the angle of the pelvis in the global co-ordinate system from the anterior most point of seat inflection.
(SIF), and the catch position. The hypothesis is that a more posterior angle would suggest the athlete initiates the catch with the trunk, less favourable for performance, while a minimal change or positive angle would indicate a stronger catch position, however may also indicate extension of the hip and knee joint without any translation of effective force from the handle to the feet.

All regression modelling followed the methodology and diagnostic testing described in Chapter 4.2.
5.2.3 Descriptive statistics of Variables for Regression analysis

Descriptive statistics for dependent variables and selected independent variables for all subjects are listed in Table 5.2.

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔLSJ</td>
<td>-2.12</td>
<td>2.61</td>
<td>0.00</td>
<td>1.46</td>
</tr>
<tr>
<td>Catch LSJ α</td>
<td>-42.35</td>
<td>1.14</td>
<td>-19.47</td>
<td>12.50</td>
</tr>
<tr>
<td>MHF LSJ α</td>
<td>-40.54</td>
<td>3.00</td>
<td>-19.30</td>
<td>12.90</td>
</tr>
<tr>
<td>Finish LSJ α</td>
<td>-32.98</td>
<td>6.05</td>
<td>-10.15</td>
<td>11.51</td>
</tr>
<tr>
<td>Catch LSJ Z</td>
<td>-306.34</td>
<td>-131.92</td>
<td>-221.35</td>
<td>48.15</td>
</tr>
<tr>
<td>MHF LSJ Z</td>
<td>97.00</td>
<td>311.71</td>
<td>200.63</td>
<td>53.68</td>
</tr>
<tr>
<td>Finish LSJ Z</td>
<td>351.98</td>
<td>503.82</td>
<td>417.79</td>
<td>40.07</td>
</tr>
<tr>
<td>Knee Up Recovery LSJ Z</td>
<td>334.43</td>
<td>499.40</td>
<td>413.25</td>
<td>41.30</td>
</tr>
<tr>
<td>Suspension 1</td>
<td>26.89</td>
<td>52.23</td>
<td>36.02</td>
<td>7.73</td>
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<tr>
<td>Suspension 2</td>
<td>137.08</td>
<td>253.93</td>
<td>193.04</td>
<td>32.34</td>
</tr>
<tr>
<td>MinSeatForceBW</td>
<td>0.08</td>
<td>0.43</td>
<td>0.25</td>
<td>0.09</td>
</tr>
<tr>
<td>Knee Up Recovery %</td>
<td>48.05</td>
<td>63.00</td>
<td>55.81</td>
<td>4.15</td>
</tr>
<tr>
<td>ΔPelvisSIF-Catch</td>
<td>-1.99</td>
<td>4.23</td>
<td>-1.08</td>
<td>1.51</td>
</tr>
<tr>
<td>MHF %</td>
<td>11.60</td>
<td>20.12</td>
<td>15.71</td>
<td>2.16</td>
</tr>
<tr>
<td>Finish %</td>
<td>24.00</td>
<td>39.00</td>
<td>32.06</td>
<td>4.06</td>
</tr>
<tr>
<td>SIF %</td>
<td>84.05</td>
<td>92.00</td>
<td>88.14</td>
<td>2.19</td>
</tr>
<tr>
<td>Handle Inflection Front %</td>
<td>87.39</td>
<td>94.00</td>
<td>91.05</td>
<td>1.68</td>
</tr>
<tr>
<td>Handle Inflection Back %</td>
<td>26.89</td>
<td>40.71</td>
<td>33.79</td>
<td>3.44</td>
</tr>
<tr>
<td>SI1 %</td>
<td>17.00</td>
<td>29.45</td>
<td>22.36</td>
<td>3.47</td>
</tr>
<tr>
<td>SI2 %</td>
<td>41.78</td>
<td>55.94</td>
<td>48.63</td>
<td>3.62</td>
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<tr>
<td>CTF</td>
<td>-6.74</td>
<td>0.68</td>
<td>-2.91</td>
<td>1.90</td>
</tr>
<tr>
<td>ΔHandle Handle Inflection Front-Catch</td>
<td>-267.56</td>
<td>-143.67</td>
<td>-192.01</td>
<td>34.20</td>
</tr>
<tr>
<td>Catch Seat Position</td>
<td>-159.94</td>
<td>197.16</td>
<td>26.94</td>
<td>96.89</td>
</tr>
<tr>
<td>Catch Handle Position</td>
<td>872.04</td>
<td>1040.41</td>
<td>953.27</td>
<td>42.36</td>
</tr>
<tr>
<td>Catch LTR</td>
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<td>1.50</td>
<td>1.00</td>
<td>0.26</td>
</tr>
<tr>
<td>MHF Seat Position</td>
<td>-500.18</td>
<td>-195.81</td>
<td>-346.06</td>
<td>80.24</td>
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<td>MHF Handle Position</td>
<td>179.79</td>
<td>451.09</td>
<td>309.50</td>
<td>66.02</td>
</tr>
<tr>
<td>MHF LTR</td>
<td>0.37</td>
<td>0.79</td>
<td>0.67</td>
<td>0.05</td>
</tr>
<tr>
<td>Finish Seat Position</td>
<td>-504.66</td>
<td>-224.85</td>
<td>-370.32</td>
<td>81.18</td>
</tr>
<tr>
<td>Finish Handle Position</td>
<td>-574.15</td>
<td>-405.46</td>
<td>-485.23</td>
<td>54.71</td>
</tr>
<tr>
<td>Finish LTR</td>
<td>0.33</td>
<td>0.40</td>
<td>0.36</td>
<td>0.02</td>
</tr>
<tr>
<td>SIF Seat Position</td>
<td>63.41</td>
<td>366.72</td>
<td>216.94</td>
<td>82.15</td>
</tr>
<tr>
<td>SIF Handle Position</td>
<td>1020.58</td>
<td>1232.90</td>
<td>1128.51</td>
<td>57.00</td>
</tr>
<tr>
<td>Handle Inflection Front Seat Position</td>
<td>40.73</td>
<td>362.54</td>
<td>201.50</td>
<td>85.36</td>
</tr>
<tr>
<td>Handle Inflection Front Handle Position</td>
<td>1050.38</td>
<td>1246.27</td>
<td>1146.95</td>
<td>51.67</td>
</tr>
</tbody>
</table>

Table 5.2: Descriptive statistics of dependent and selected independent variables

Table 5.2 shows the ΔLSJ variable to vary between increased flexion and extension by approximately ±2° of a 0 mean. LSJα is typically flexed by 19° at catch and MHF, less so at the finish with a mean of 10°. Positions of LSJ Z varied, but all with similar standard
deviation values, as would be expected in tested subjects of different heights and limb lengths.

MinSeatForce/BW was typically 0.25 times body weight, but with some values significantly higher or lower than this.

The mean timing of knee up on the recovery was at 56%, with values ranging from 48 to 63%. Timing of MHF was 15%, Finish 32%, SIF was 88%, Handle Inflection Front 91% and Handle Inflection Back 34%. SI1 occurred at 22%, SI2 48%. Stroke timing profiles at the catch were subject to a lower standard deviation than those during the drive and finish, suggesting that athletes respond during the drive in different ways. This was also suggested by Suspension 2, total drive suspension, which was significantly more varied than Suspension 1, suspension from catch to MHF. CTF was typically -3%, indicating handle inflection front to be 3% later than the seat inflection in this section of the stroke cycle. However, some athletes exhibited significantly greater delay than others, known as ‘shooting the slide’, where the seat moves before the handle, while another changed direction of the handle before the seat, which can only occur through either flexion of the upper body or initiating the drive with posterior rotation of the pelvis.

LTR at the catch was typically exactly 1.00, with a standard deviation of 0.26, indicating equal displacement of seat and handle at the catch, however some subjects scored 0.54 and 1.50 indicating seat travel 54% and 150% that of handle travel, which require significantly different rowing technique to produce. An LTR closer to 1 would suggest an improved timing of the catch. LTR at MHF mean was 0.67, ranging from 0.57 to 0.79, showing athletes reach a position of MHF with different proportions of leg and trunk application. Finish LTR ranges of 0.33 to 0.40 were outside the mean of 0.36 and SD of 0.02, indicating a variation of finish position. The source may be posterior pelvic rotation, extension of the LSJ, or displacing the handle higher on the body (with increased posterior rotation of the trunk, more space is available for the handle to be displaced, as the chest or head of the athlete will no longer limit handle travel).
The angle change of the pelvis from the inflection of the seat was typically 1° of posterior rotation, but ranged from 4° anterior rotation to 2° posterior rotation.

5.2.4 Outputs of Regression Modelling

The results from the regression analysis is divided into 2 sections. This section, 5.2.4, shows the outputs of the regression analysis for each dependent variable, Section 5.3 summarises the collective output of these models.

In this section, the process and output of the regression models follows the methodology described in Chapter 3. The process, from selection of independent variables to testing and validating the linear regression model and the final regression coefficients is presented step-by-step for the first example, ΔLSJ catch – MHF. This dependent variable, is a pertinent performance indicating parameter in previous literature, and describes the change in angle of the LSJ from the catch to MHF. For the remaining dependent variables, the outputs of the developed regression models are shown, with the details of validity testing etc. presented in Appendix D – Results of Regression Analysis.

Regression models for MHF LSJ Z, Suspension 2, LSJ α finish and lumbar pelvic ratios at the catch, MHF and finish did not pass any one or more of the required checks in the construction or validation of linear regression modelling, and will not be discussed further.

5.2.4.1 ΔLSJ catch – MHF

With the dependent variable ΔLSJ catch – MHF selected, forward stepwise linear regression modelling was applied, using the independent variables listed in Table 5.1 and Table 5.2. The inclusion and removal of independent variables was selected using both the Best Subsets method, where all potential individual variables and all potential combinations are considered and included and removed based on F-statistics, excluding effects with p-values less than 0.05. Having removed all but 5 of the independent variables, the model was repeated using the enter method of multiple linear regression. If the model did not meet the criteria of validity outlined Statistical methodology Chapter 4.2, the model was to be rejected or modified and tested again until it is rejected or meets the required criteria.
For ΔLSJ catch – MHF the regression modelling extracted 5 variables, achieving an $R^2 = 0.864$, adjusted $R^2 = 0.839$. This accounts for 83% of the variance in the dependent variable, and a good ability to predict with a highly significant F value of 34.3 ($P<0.001$). Cook’s distance was at most 0.056, and Mahalonobis 3.1 and mean leverage of 0.152. These scores were not problematic.

Residuals of the regression analysis are plotted in Figure 5-7, with a mean of -0.03. Assumptions of normality, homoscedasticity and auto correlation have been satisfied. Errors are suggested to be independent, and multi-collinearity was not present from a Durbin-Watson test score of 2.163, and a maximum VIF of 1.13.

![Figure 5-7: Assessment of normality and constant variance in the regression model for ΔLSJ catch – MHF](image)

The linear relationship between the variables in Figure 5-8 that produce the model can explain 83% of the variance in ΔLSJ catch – MHF, with a standardised error of estimate of 0.59°.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Unstandardised</th>
<th>Standard Error</th>
<th>Standardised</th>
<th>t-test</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>constant</td>
<td>20.006</td>
<td>3.413</td>
<td></td>
<td>5.862</td>
<td>0.00</td>
</tr>
<tr>
<td>HandleΔ – Handle Inflection</td>
<td>-0.024</td>
<td>0.004</td>
<td>-0.555</td>
<td>-6.430</td>
<td>0.00</td>
</tr>
<tr>
<td>Finish COP</td>
<td>0.766</td>
<td>0.098</td>
<td>0.651</td>
<td>7.792</td>
<td>0.00</td>
</tr>
<tr>
<td>S1I</td>
<td>-0.171</td>
<td>0.037</td>
<td>-0.405</td>
<td>-4.613</td>
<td>0.00</td>
</tr>
<tr>
<td>MHF/Body mass</td>
<td>-0.169</td>
<td>0.080</td>
<td>-0.173</td>
<td>-2.116</td>
<td>0.04</td>
</tr>
<tr>
<td>MHF LTR</td>
<td>-23.507</td>
<td>3.164</td>
<td>-0.800</td>
<td>-7.429</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Figure 5-8: Significant (P<0.05) predictors of ΔLSJ catch – MHF derived from linear regression model

This model for ΔLSJ catch – MHF suggests that increased flexion of the spine during the drive of the rowing stroke is associated with increased distance of handle travel before the catch occurs, a more anterior position on the seat at the finish, a descriptive variable of handle force normalised by mass, and the LTR at MHF, a lower relative travel of the seat compared to the handle.

In more accessible terminology; increased flexion of the spine has been shown to be deliterious to performance outputs, and this has been shown to be significantly more likely when 6 non-three dimensional parameters meet certain conditions. Less flexion of the spine occurs when the handle travel is minimised from its most forward position to the position at which significant propulsive force is applied to the handle. Less spine flexion occurs when the athletes body weight is closer to the rear of the seat at the finish of the stroke, timing of the end of the completion of the leg drive to be later on within the stroke, and a higher ratio of peak handle force to body weight. Finally, indicated by the LTR value at peak handle force, reduced flexion occurs when the seat and handle move in sync during the drive phase, with increased spinal flexion when the handle moves further relative to the travel of the seat.

5.2.4.2 Catch LSJ α

With the dependent stroke profile variable Catch LSJ α, the data reduction and regression methodology extracted 4 variables, as listed in Table 1.1. The linear regression model using
these variables has an adjusted $R^2 = 0.767$, and met non-problematic criteria tests, as shown in Appendix D – Results of Regression Analysis, 7.4.1 Catch LSJ $\alpha$. This model accounts for 76% of the variance in Catch LSJ $\alpha$, with a standard error of estimate of 6.0°.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unstandardised</th>
<th>Standard Error</th>
<th>Standardised</th>
<th>t-test</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Constant)</td>
<td>-53.468</td>
<td>11.115</td>
<td>-4.810</td>
<td>.000</td>
<td></td>
</tr>
<tr>
<td>SI1 COP</td>
<td>6.364</td>
<td>.591</td>
<td>1.149</td>
<td>10.762</td>
<td>.000</td>
</tr>
<tr>
<td>Finish %</td>
<td>2.656</td>
<td>.425</td>
<td>.863</td>
<td>6.256</td>
<td>.000</td>
</tr>
<tr>
<td>SI1 %</td>
<td>-1.238</td>
<td>.410</td>
<td>-3.019</td>
<td>.005</td>
<td></td>
</tr>
<tr>
<td>MHF/BM</td>
<td>-1.597</td>
<td>.701</td>
<td>-.192</td>
<td>-2.280</td>
<td>.030</td>
</tr>
</tbody>
</table>

Table 5.3: Significant ($P<0.05$) predictors of Catch LSJ $\alpha$ derived from linear regression model

Flexion of the lumbar spine is influenced by a more anterior centre of pressure of the athlete on the seat at the point at which the seat begins to move in the posterior direction, and also the stroke profile of the finish occurring later in the stroke. An earlier Seat inflection point 1, so the point at which the leg drive has been completed occurring earlier, and a lower ratio of MHF/BM have a positive influence on increased LSJ flexion.

5.2.4.3 LSJ $\alpha$ MHF

With the dependent stroke profile variable MHF LSJ $\alpha$, the data reduction and regression methodology extracted 3 variables, listed in Table 5.4. The linear regression model using these variables has an adjusted $R^2 = 0.730$, and met non-problematic criteria tests, as shown in Appendix D – Results of Regression Analysis, 7.4.2 LSJ $\alpha$ MHF. This model accounts for 73% of the variance in MHF LSJ $\alpha$, with a standardised error of 6.7°.
Table 5.4: Significant (P<0.05) predictors of MHF LSJ α derived from linear regression model

<table>
<thead>
<tr>
<th>Variable</th>
<th>Regression coefficients</th>
<th>t-test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unstandardised</td>
<td>Standardised</td>
</tr>
<tr>
<td>(Constant)</td>
<td>-65.112</td>
<td>-6.226</td>
</tr>
<tr>
<td>SI1 Cop</td>
<td>6.389</td>
<td>1.118</td>
</tr>
<tr>
<td>Finish %</td>
<td>2.473</td>
<td>.779</td>
</tr>
<tr>
<td>SI1 %</td>
<td>-1.274</td>
<td>-.342</td>
</tr>
</tbody>
</table>

Flexion in LSJ at the point of maximum handle force is increased through a more anterior centre of pressure at the anterior most inflection point of the seat, a later occurrence of the finish of the stroke (defined by handle force) and an earlier point of SI1, or an earlier expiry of the drive phase where the legs contribute to the stroke.

5.2.4.4 Catch LSJ Z

With the dependent stroke profile variable LSJ Z catch, the data reduction and regression methodology extracted 3 variables, listed in Table 5.5. The linear regression model using these variables has an adjusted $R^2 = 0.842$, and met non-problematic criteria tests, as shown in Appendix D – Results of Regression Analysis, Catch LSJ Z. This model can predict 84% of the variance in LSJ Catch Z, with a standard error of 19.2.mm.

Table 5.5: Significant (P<0.05) predictors of LSJ Z Catch derived from linear regression model

<table>
<thead>
<tr>
<th>Variable</th>
<th>Regression coefficients</th>
<th>t-test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unstandardised</td>
<td>Standardised</td>
</tr>
<tr>
<td>(Constant)</td>
<td>523.32</td>
<td>-6.47</td>
</tr>
<tr>
<td>Catch Handle Position</td>
<td>-0.70</td>
<td>-0.61</td>
</tr>
<tr>
<td>SIF Seat Position</td>
<td>-0.25</td>
<td>-0.43</td>
</tr>
<tr>
<td>Posterior Δ Seat from SI1</td>
<td>1.03</td>
<td>0.22</td>
</tr>
</tbody>
</table>

More posterior handle position at the catch, seat position at the SIF position, and change in seat position from SI1 and 2 result in a more anterior prediction for LSJ Z catch.
5.2.4.5 **Finish LSJ Z**

With the dependent stroke profile variable LSJ Z Finish, the data reduction and regression methodology extracted 5 variables, listed in Table 5.6. The linear regression model using these variables has an adjusted $R^2 = 0.828$, and met non-problematic criteria tests, as shown in Appendix D – Results of Regression Analysis, 7.4.4 Finish LSJ Z. This model can predict 82% of the variance in LSJ Finish, with a standardised error of estimate of 19.0mm.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Regression coefficients</th>
<th>t-test</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Constant)</td>
<td>443.5</td>
<td>6.0</td>
<td>0.000</td>
</tr>
<tr>
<td>SIF Handle Position</td>
<td>-0.3</td>
<td>-7.7</td>
<td>0.000</td>
</tr>
<tr>
<td>MHF Handle Position</td>
<td>-0.5</td>
<td>-8.5</td>
<td>0.000</td>
</tr>
<tr>
<td>Seat Δ - Seat Inflection to Catch</td>
<td>0.3</td>
<td>5.8</td>
<td>0.000</td>
</tr>
<tr>
<td>MHF LTR</td>
<td>681.3</td>
<td>8.7</td>
<td>0.000</td>
</tr>
<tr>
<td>Finish Handle Position</td>
<td>-0.1</td>
<td>-2.9</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Table 5.6: Significant (P<0.05) predictors of LSJ Z Finish derived from linear regression model

Prediction outputs of the model with higher values for LSJ Z Finish are associated with a more posterior handle position at SIF, MHF and Finish. A higher LTR (ratio of seat to handle travel from the foremost inflection point of each), and posterior displacement of the seat after the SIF position.

5.2.4.6 **Knee Up LSJ Z**

For dependent stroke profile variable LSJ Z Knee Up, the data reduction and regression methodology extracted 3 variables, listed in Table 5.7. The linear regression model using these variables has an adjusted $R^2 = 0.661$, and met non-problematic criteria tests, as shown in Appendix D – Results of Regression Analysis, 7.4.5 Knee Up LSJ Z. This model can predict 66% of the variance in LSJ Knee Up, with a standard error of estimate of 24.1mm.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Regression coefficients</th>
<th>t-test</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Constant)</td>
<td>406.093</td>
<td>10.341</td>
<td>.000</td>
</tr>
<tr>
<td>Finish Seat Position</td>
<td>-.346</td>
<td>-6.816</td>
<td>.000</td>
</tr>
<tr>
<td>MHF/BM</td>
<td>-8.717</td>
<td>-3.154</td>
<td>.003</td>
</tr>
<tr>
<td>Anterior Δ COP from SI1-SI2</td>
<td>-5.987</td>
<td>-2.443</td>
<td>.020</td>
</tr>
</tbody>
</table>

Table 5.7: Significant (P<0.05) predictors of Catch LSJ Z derived from linear regression model LSJ Z Knee Up

The regression model will produce more anterior LSJ Z catch predictions with more anterior seat positions at the fish, a lower ratio of maximum handle force to body mass, and more posterior change in COP on the seat from the first to second inflection of seat travel.

5.2.4.7 Suspension 1

With the dependent stroke profile variable Suspension 1, the data reduction and regression methodology extracted 4 variables, listed in in Table 5.8. The linear regression model using these variables has an adjusted $R^2 = 0.775$, and met non-problematic criteria tests, as shown in Appendix D – Results of Regression Analysis, 5.2.4.7 Suspension 1. This model can predict 77% of the variance in Suspension 1, with a standard error of estimate of 3.7.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Regression coefficients</th>
<th>t-test</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Constant)</td>
<td>-46.796</td>
<td>-1.217</td>
<td>0.233</td>
</tr>
<tr>
<td>MHF Handle Position</td>
<td>-0.082</td>
<td>-8.406</td>
<td>0.000</td>
</tr>
<tr>
<td>Seat Inflection Occurs Front</td>
<td>1.392</td>
<td>3.353</td>
<td>0.002</td>
</tr>
<tr>
<td>SI2 Cop</td>
<td>-2.219</td>
<td>-5.642</td>
<td>0.000</td>
</tr>
<tr>
<td>MHF/BM</td>
<td>-1.402</td>
<td>-3.226</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Table 5.8: Significant (P<0.05) predictors of Suspension 1 derived from linear regression model

Suspension 1, was positively related to a more posterior handle position at MHF, a later
inflection of the seat with respect to the percentage stroke scale, a more posterior COP at SI1, and a negative relationship with the ratio of MHF to subject mass.

5.2.4.8 **Min Seat Force**

For dependent stroke profile variable MinSeatForce/BW, the data reduction and regression methodology extracted 4 variables, listed in Table 5.9. The linear regression model using these variables has an adjusted $R^2 = 0.701$, and met non-problematic criteria tests, as shown in Appendix D – Results of Regression Analysis, 7.4.7 Min Seat Force. This model can predict 70% of the variance MinSeatForce/BW, with a standard error of 0.1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Regression coefficients</th>
<th>t-test</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Constant)</td>
<td>-46.8</td>
<td>38.5</td>
<td>-1.2</td>
</tr>
<tr>
<td>MHF Position</td>
<td>-0.1</td>
<td>0.0</td>
<td>-0.7</td>
</tr>
<tr>
<td>SIF %</td>
<td>1.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>SI1 COP</td>
<td>-2.2</td>
<td>0.4</td>
<td>-0.6</td>
</tr>
<tr>
<td>MHF/BM</td>
<td>-1.4</td>
<td>0.4</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

**Table 5.9**: Significant (P<0.05) predictors of Min Seat Force derived from linear regression model

MinSeatForce/BW was increased with more posterior handle position at MHF, a later stroke profile variable for seat inflection, a more anterior COP at SI1, and a lower MHF/BM ratio.

5.2.4.9 **Knee up Recovery %**

With the dependent stroke profile variable Knee up recovery %, the data reduction and regression methodology extracted 4 variables, listed in Table 5.10. The linear regression model using these variables has an adjusted $R^2 = 0.864$, and met non-problematic criteria tests, shown in Appendix D – Results of Regression Analysis, 7.4.8 Knee up Recovery %. This model can predict 86% of the variance in Knee Up Recovery %, with a standard error of 1.5%.
Table 5.10: Significant (P<0.05) predictors of Knee up Recovery % derived from linear regression model

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unstandardised</th>
<th>Standard Error</th>
<th>Standardised</th>
<th>t-test</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Constant)</td>
<td>39.66</td>
<td>10.58</td>
<td>1.07</td>
<td>3.75</td>
<td>0.00</td>
</tr>
<tr>
<td>SI1</td>
<td>1.22</td>
<td>0.16</td>
<td>-0.51</td>
<td>7.84</td>
<td>0.00</td>
</tr>
<tr>
<td>SIF Handle Position</td>
<td>-0.04</td>
<td>0.01</td>
<td>-0.24</td>
<td>-6.53</td>
<td>0.00</td>
</tr>
<tr>
<td>Catch COP</td>
<td>0.64</td>
<td>0.21</td>
<td>0.24</td>
<td>3.02</td>
<td>0.01</td>
</tr>
<tr>
<td>SI2 Handle Position</td>
<td>-0.01</td>
<td>0.00</td>
<td>-0.43</td>
<td>2.82</td>
<td>0.01</td>
</tr>
<tr>
<td>Step</td>
<td>-0.36</td>
<td>0.31</td>
<td>-0.10</td>
<td>-1.13</td>
<td>0.17</td>
</tr>
<tr>
<td>Gender</td>
<td>-1.44</td>
<td>0.59</td>
<td>-0.17</td>
<td>2.43</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Step was included as a factor to account for the inherent change in timing of a stroke profile point such as Knee up Recovery %. Raising the knees later in the stroke (the onset of KJC flexion) was predicted by a later timing of the inflection of the seat after the finish of the stroke, a handle that is further away from the ergometer head when the seat changes direction at the front of the stroke, and a more posterior COP at the catch. Step and female subjects were factors reducing the predicted values for Knee up Recovery %.

5.2.4.10 ΔPelvis° SIF to Catch

For dependent stroke profile variable ΔPelvis° SIF to Catch, the data reduction and regression methodology extracted 4 variables, listed in in Table 5.11. The linear regression model using these variables has an adjusted $R^2 = 0.661$, and met non-problematic criteria tests, as shown in Appendix D – Results of Regression Analysis, 7.4.9 ΔPelvis° SIF to Catch. This model can predict 66% of the variance in ΔPelvis° SI2 to Catch, with a standard error of estimate of 0.9°.
### 5.3 Summary of Regression Results

19 unique variables were used within the ten sets of analyses that produced regression models. Seat position was included (either directly or as a stroke point where another variable was recorded) in 26 (62%) and 12 (63%) of the total and unique predictor variables. Handle position was included in 14 (33%) and 6 (32%) of the total and unique predictors. Centre of Pressure was included in 11 (58%) and 5 (26%) of total and unique predictors, while handle force was included in 18 (42%) of total and 9 (47%) of the regression model predictors.

An aim of this study was to examine if 3D kinematic variables can be predicted only using ‘simple’, non-three dimensional kinematic measurements. Valid models for ten 3D dependent kinematic parameters, identified in previous research to act as predictors of performance or of interest to individuals in the sport were developed using ergometer instrumentation alone. 66 to 86% of variance of the ten performance influencing variables was accounted for in the regression models created from the data captured for this study.
Table 5.12 summarises the outputs of this analysis, and serves two functions: First, to shown in descending order the independent variables that were included in the most valid regression models to predict known performance parameters. Secondly, favourable values, timings, movements etc. of the non-three dimensional kinematic measurements is suggested, having considered the directions and/or quantities of the performance parameters considered beneficial for performance by this study and past literature. These suggestions based on the regression modelling in this study indicate favourable movement and forces at the seat, handle etc. and is described in more detail, and simpler terminology in Table 5.13.
### Table 5.1.2: Summary of Outputs from Regression Analyses

19 non 3D kinematic variables were used in regression models of the performance parameters listed. Standardised Regression Coefficient is shown to illustrate the negative or positive relationship with dependent variable. Suggested improved performance motion listed.
<table>
<thead>
<tr>
<th>Non 3D kinematic variable</th>
<th>Motion for improved performance</th>
<th>In simpler terminology:</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHF/BM</td>
<td>Increase Ratio</td>
<td>Higher ratio of peak handle force to athlete body mass. Therefore, increase force production, and/or lower body mass.</td>
</tr>
<tr>
<td>SIF Handle Position</td>
<td>More anterior handle position</td>
<td>Keep handle forward when the seat starts to drive back at the catch.</td>
</tr>
<tr>
<td>S11 COP</td>
<td>More Posterior COP</td>
<td>As the leg drive is completed, the athlete body mass should be relatively more toward the back of the seat.</td>
</tr>
<tr>
<td>MHF Handle Position</td>
<td>More Anterior handle position</td>
<td>Handle is further forward when peak handle force achieved.</td>
</tr>
<tr>
<td>SI2 Handle Position</td>
<td>More Anterior handle position</td>
<td>The change of the direction of the seat at the start of the recovery (onset of knee joint flexion) occurs later in the stroke.</td>
</tr>
<tr>
<td>SI2 %</td>
<td>Inflection Later in Stroke</td>
<td>The end of the leg drive (seat reaches maximum posterior position) occurs later in the stroke.</td>
</tr>
<tr>
<td>SI1 %</td>
<td>Inflection Later in Stroke</td>
<td>Timing the backward (posterior) motion of the seat, i.e. the drive of the legs, before the onset of handle force. Or in other words, move the seat before the handle.</td>
</tr>
<tr>
<td>Catch Cop</td>
<td>Less Anterior COP</td>
<td>Body mass further backward on the seat at the catch.</td>
</tr>
<tr>
<td>Finish %</td>
<td>Inflection Later in Stroke</td>
<td>Maintaining handle force for longer in the stroke.</td>
</tr>
<tr>
<td>SIF %</td>
<td>Earlier inflection (relative to the catch)</td>
<td>At the point of peak handle force, the seat further from the catch than the handle.</td>
</tr>
<tr>
<td>MHF LTR</td>
<td>Higher ratio of seat/handle, or leg/trunk utilisation</td>
<td>From the end of the leg drive, but before the flexion of the knees, the seat doesn’t move forward. This would suggest the athlete is slumping at the finish, i.e. lumbar-pelvic flexion, allowing the seat to move forward.</td>
</tr>
<tr>
<td>Posterior Δ Seat from SI1- SI2</td>
<td>More anterior seat Δ before SI1</td>
<td>Minimising the movement of the handle before force is applied to the handle. Poor performance would occur when the handle moves without force being applied.</td>
</tr>
<tr>
<td>Handle Δ – Handle Inflection-Catch</td>
<td>Less Anterior handle Δ before the Catch</td>
<td>As handle force application ends (finish of stroke) the seat being further forward.</td>
</tr>
<tr>
<td>Finish Seat Position</td>
<td>Less Posterior Finish seat position</td>
<td>At the catch, the handle further forward.</td>
</tr>
<tr>
<td>Catch Handle Position</td>
<td>More anterior handle position at catch</td>
<td>At the finish, centre of mass of athlete toward the front of the seat.</td>
</tr>
<tr>
<td>Finish COP</td>
<td>More anterior Finish COP</td>
<td>When force applied to the handle, the seat should not be moving forward, ideally backward (i.e. leg drive).</td>
</tr>
<tr>
<td>Seat Δ - Seat Inflection to Catch</td>
<td>More anterior seat Δ before catch</td>
<td>Athlete centre of mass more forward at the onset of knee flexion.</td>
</tr>
<tr>
<td>Anterior Δ COP from SI1- SI2</td>
<td>More anterior COP achieved at Seat Inlect 2</td>
<td>Athlete centre of mass more forward at the onset of knee flexion.</td>
</tr>
<tr>
<td>S12 Cop</td>
<td>More Anterior COP</td>
<td>Athlete centre of mass more forward at the onset of knee flexion.</td>
</tr>
</tbody>
</table>

Table 5.13: Explanation of the suggested motions for improved performance suggested in Table 5.12
Chapter 6  Discussion

6.1  Discussion of Descriptive Measures

The aims of this thesis were to identify opportunities to improve the measurement of kinematics of ergometer rowing, and investigate if such measurements had a potential to predict other variables. It was hypothesised that predictions could be made for kinematic variables describing rowing technique and motion that normally require direct measurement using an instrumented ergometer. In meeting the objectives set to perform this investigation, for the first time the motion of an ergometer seat with respect to a wider range of kinematic and kinetic measurements has been measured. The seat position sensor was validated to measure to an accuracy of ±1mm, and it was demonstrated to reliably identify the motion of the ergometer seat in three assessments of reliability; within individual sets of rowing strokes, between the sets of rowing strokes grouped by test step (intensity) and by athlete group (e.g Light Weight Male). These assessments covered normal and atypical movements of the seat, equal to and beyond the normal and maximum displacements, velocities and accelerations exhibited during ergometer rowing.

Motion was investigated between stroke rates as part of a step test consisting of four sets of three minute steps, of increasing intensity of exertion. The motion of the ergometer seat was shown to move with three distinct points of inflection during the rowing stroke. Starting at the catch of the stroke, where the user, and the seat is at the most anterior position of travel, seat inflection front (SIF) occurs before the catch. In this study the catch is defined by the onset of handle force, and each stroke cycle was normalised by the catch point into a 0-100% cycle, where 0% represents the catch. Seat inflection, SIF, would occur 10% earlier than the catch during the lower rate and intensity step of the protocol, and 15% earlier at the highest intensity step RMAX. The mean position for SIF for all rates was 88% (N.B. in this study 4 of the 14 athlete subjects did not complete all rate steps, hence this mean SIF calculation only includes subject data sets that completed the full protocol). The next point of inflection SII, occurred at a mean of 23% which was 7% after the position of maximum handle force and a mean of 10% before the finish of the stroke (based on the end of propulsive handle force). This peak seat displacement occurs when the knee and ankle joint are relatively fully extended, and the legs are no longer contributing to the application of propulsive force.
Referring back to the stroke profile diagrams in Figure 1-1, SI2 shows the point during the drive phase when the leg drive has completed, with the full extension of the hip joint and flexion of the arms remaining to be completed and the finish position reached. The seat initiated its recovery toward the catch at SI2, occurring when the seat was at its most posterior position at the moment it begins anterior motion. SI2 occurs at a mean of 26% of the stroke after SI1, 16% after the finish, 15% after the posterior most inflection point of the handle, and 7% before the onset of knee joint flexion. Timing of SI1 and SI2 did not vary significantly between LWM and HWW or by intensity of effort. As opposed to the timing, the measurement of seat position at SI1 in the global coordinate system did vary between athlete groups and with a large standard deviation. SI1 measurements are the points at which the leg drive finishes, and whilst their timing represents technical variation, measurement variations are due to the difference in anthropometrics between individuals and groups. It was a surprising outcome to observe anterior motion of the seat between SI1 and SI2, and this varied significantly between athletes and by intensity of effort.

The inflection and travel of the handle was also found to vary, and occur before the onset of handle force. The mean timing was 9% before the catch. Thus in this elite population of athletes, the seat moved in a posterior direction before the handle.

The difference in timing between the inflection of the seat and handle corresponds to previous research by Murphy (2009) which identified variation in the timing of the position of maximum handle force and the finish of the stroke. A later timing of the finish of the stroke in that study was identified as being beneficial for performance outputs. McGregor et al. (2004) compared different athlete technique faults during ergometer rowing, discussing their potential influence on performance and injury risk. These athlete technique faults, illustrated in Figure 6-1, such as ‘slide shooting’ where the seat moves more than the handle, and the opposite fault of initiating the stroke with the trunk rather than an equal application of handle and seat can be identified through the measure of the timing of the handle and seat.
To account for variations of limb length and overall height, two novel measures of the relative position of handle and seat were introduced and described. The timing difference in the inflection points of the seat and handle at the most anterior part of the stroke, just before the catch, was defined as the Catch Timing Factor. The mean value was -3%, illustrating athletes in this trial initiated movement of the seat before the handle. Given the elite classification of the subjects, and their inherent high performance outputs within the rowing population, it is proposed that this may be within an optimum range. This is suggested as a positive value would indicate handle travel before the catch, and the movement of the seat, implying that movement occurring would be in the arms and/or trunk. Such sequencing of movement is deemed less effective than a more synchronised motion of seat and handle (Nolte, 2011).

In this study, handle travel before the catch indicated less favourable performance outputs. These were; reduced total propulsive force applied to the handle, a shorter length of time applying propulsive force and reduced suspension from the seat, in agreement with current technical coaching and documented rowing biomechanics research. In this study the timing of the handle inflections varied significantly between rate steps, with the timing of the seat less so. Earlier motion of the handle than the seat indicates a lower transfer of force through the body, indicated by shorter force application during the stroke, and less of the athlete weight

---

**Figure 6-1: Diagram of relative handle and seat motion**

<table>
<thead>
<tr>
<th>Coordinated handle and seat motion</th>
<th>Seat motion &gt; handle motion a.k.a ‘slide shooting’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handle travel &gt; Seat travel a.k.a ‘tugging handle’, n.b. this example shows handle travel due to a combination of flexion of the upper limb and spine, and extension of the hip</td>
<td></td>
</tr>
</tbody>
</table>

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---
lifting off the seat (suspension). The movement of the arms and/or trunk also means a proportion of the sequence of the rowing stroke has been completed without contributing to propulsive force and thus is relatively deleterious to performance.

The relative travel of the seat and handle is quantified in the measure defined as Leg Trunk Ratio. This can quantify the relative position of the seat and handle, each relative to their own inflection point. This measurement at the catch, MHF and finish can describe the relative use of the lower and upper body, where values less than 1 describe a higher relative use of the upper body (however it is unknown what individual or combination of specific movements within the upper body are involved as this region is not instrumented). Scores greater than 1 indicate a higher use of the lower body than the upper body.

The difference in timing of the handle and seat in this subject group was subject to more variation at the catch than the finish, suggesting the catch of the stroke is subject to greater variations in technique, or limitations due to flexibility than any other position in the stroke.
6.2 Outputs of Regression Modelling

Using measures of ergometer instrumentation alone; a combination of handle position, seat position, handle force and force on the ergometer seat, models to describe the dependent variables in Table 6.1 were shown to meet satisfactory tests of regression modelling, and account for the variance as listed.

<table>
<thead>
<tr>
<th>ΔLSJ α catch to</th>
<th>Adj R²</th>
<th>Standard error of estimate</th>
<th>Mean Observed Measurement</th>
<th>Standard Deviation Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHF</td>
<td>0.83</td>
<td>0.59</td>
<td>0.00</td>
<td>1.46</td>
</tr>
<tr>
<td>Catch LSJ α</td>
<td>0.76</td>
<td>6</td>
<td>-19.47</td>
<td>12.5</td>
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<tr>
<td>MHF LSJ α</td>
<td>0.73</td>
<td>6.7</td>
<td>-19.3</td>
<td>12.9</td>
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<tr>
<td>Catch LSJ Z</td>
<td>0.84</td>
<td>19.2</td>
<td>-221.35</td>
<td>48.15</td>
</tr>
<tr>
<td>Finish LSJ Z</td>
<td>0.82</td>
<td>19</td>
<td>417.79</td>
<td>40.07</td>
</tr>
<tr>
<td>Knee up LSJ Z</td>
<td>0.66</td>
<td>24.1</td>
<td>413.25</td>
<td>41.3</td>
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<tr>
<td>Suspension 1</td>
<td>0.77</td>
<td>3.7</td>
<td>36.02</td>
<td>7.73</td>
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<tr>
<td>Min seat force/BW</td>
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<td>0.1</td>
<td>0.25</td>
<td>0.09</td>
</tr>
<tr>
<td>Knee up</td>
<td>0.86</td>
<td>1.5</td>
<td>55.81</td>
<td>4.15</td>
</tr>
<tr>
<td>Recovery %</td>
<td>0.66</td>
<td>0.9</td>
<td>-1.08</td>
<td>1.51</td>
</tr>
</tbody>
</table>

Table 6.1: Predictive ability of regression models, standard error and the mean and standard deviation of the observed measurements

6.2.1 Non-3D kinematic indicators of improved performance

The independent variables and the suggested beneficial movements for improved performance consisted of 4 stroke profile timing parameters; Seat Inflection 1 %, Seat Inflection 2 %, Finish %, Seat Inflection Front %; The position of the handle at 5 points of the stroke; catch, MWF, Seat Inflection 2 and Seat Inflection Front; The relative travel of the handle from Seat Inflection Front to Catch; The relative travel of the seat from Seat Inflection Front to catch; The relative travel of the seat and handle to form the Leg Trunk Ratio; The value of maximum handle force normalised by body mass, and the centre of pressure of the force applied to the ergometer seat at the catch, seat inflection 1, seat inflection 2.
Five of the 3D kinematics predicted in Table 6.1, and their suggested directions were also demonstrated to be favourable for performance improvements by Murphy (2009); reduced flexion of L5/S1 at the catch, MHF, and minimising the total change between the catch and MHF. LSJ Z at the catch was shown to be favourable in a more posterior position, and a more anterior position at MHF, whilst more posterior at knee up. Suspension was used as positive performance output. Buckeridge et al. (2012) demonstrated that greater hip flexion around the catch as being important to the generation of propulsive foot force during ergometer rowing. When these are considered in relation to Table 6.1 and the regression models they formed, favourable directions of motion were estimated for the non-3D variables listed:

a. An increased ratio of MHF/BM. This is unremarkable; higher performance is linked to a normalised maximum force output.
b. More anterior handle position at the most anterior position of the seat. This would influence stroke length, however may also be considering initiating the stroke with the handle, not the lower body.
c. More posterior centre of pressure on the seat at SI1. In relation to high suspension 1 values, a more posterior COP at this point may indicate greater suspension and force transfer from seat to handle.
d. More anterior handle position at MHF. See e.
e. Higher ratio of seat/handle travel (LTR) at MHF. This suggests higher performance when the trunk and pelvis remain in more anterior rotation and the upper body displaces less than the lower body. This will improve suspension, as well as the proportion of upper body that can still be used to apply force to the handle once the leg drive has completed (SI1).
f. SI1 and SI2 timing occurring later in the stroke, these suggest that the completion of the leg drive (SI1) and the initiation of the recovery is performed later in relation to higher performance. This is suggested due to a more effective catch and increased suspension; the speed of the drive is lower but a more effective stroke is undertaken.
g. More anterior COP at finish, more posterior COP at the catch. In addition to the other COP values, and the relation of COP to the regression models at the knee up % in the recovery, and the change of angle of the pelvis approaching the catch position, it is suggesting that the combination of seat position and force on the seat has allowed the
models to account for the anterior and posterior rotation of the pelvis, at the finish and catch of the stroke. The ability of the models to predict the timing of the onset of knee joint flexion on the recovery of the stroke, the position of the LZJ at this timing point, and the levels of suspension achieve suggest COP is a valuable addition to the predictive capacity of these models.

h. Finish % occurring later in the stroke.
i. Seat Inflection Front occurring earlier relative to catch.
j. More anterior seat inflection SI.
k. Less anterior handle before catch. Less anterior travel before the catch occurs and propulsive force is being applied to the handle suggests that initiating the stroke with the upper body as being deleterious to performance.
l. More anterior seat position at finish.

6.2.2 Predictive Relationships developed

The regression models, and their outputs shown in Table 6.1 could account for 66-86% of the variance in selected measurements, with significant accuracy, using measurements of the rowing ergometer alone. Measurements such as the timing of knee flexion during the recovery of the stroke and the range of spinal flexion during the drive have been shown in past literature to be significant performance parameters, as well as suggested to be indicative of injury risk. These two measurements, that would otherwise require direct measurement of the user of a rowing ergometer could be estimated with a confidence of 83 and 86%, with a standard error of 0.59° and 1.5% respectively.

The regression models that make these predictions are subject to the range of limitations of this study, the discussion of which follows within this Chapter. A regression model created using one subset of data, in this case 1 cohort of 14 elite athletes tested for a total of 12 minutes over 4 levels of intensity and stroke rates.

The number of subjects tested in this study was 14, and while the regression models produced satisfied predetermined diagnostic tests, this was only for the sample within this study. With a greater sample size, a subset of the sample could have been excluded from the dataset input for regression analysis and once an appropriate model created it could then be reapplied on the excluded datasets to test the validity of the model. Whilst this was not possible in this
study, the relationships developed have correlated and corresponded to aspects of other relevant research. The discussion of other limitations such as fatigue, consistency etc. will follow later in this Chapter.

Despite the limitations of the study, the relationships developed have shown the hypothesis that kinematic measurements that typically require complex motion capture equipment can be predicted using simpler kinematic and kinetic measurements of the ergometer alone.

If the two regression models $\Delta LSJ\,\alpha$ catch to MHF and for Knee up Recovery % are considered, the regression models have an adjusted $R^2$ of 0.83 and 0.86, the independent variables that produce these models are listed in Table 6.2.

<table>
<thead>
<tr>
<th>Adj $R^2$</th>
<th>Independent Variables that formed regression model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta LSJ,\alpha$ catch to MHF</td>
<td>0.83</td>
</tr>
<tr>
<td>Knee up Recovery %*</td>
<td>0.86</td>
</tr>
</tbody>
</table>

*Intensity of effort and gender were factors in this model

This demonstrates that if the ergometer seat and handle were to be instrumented for position and force measurement, the change in angle of the lumbar spine during the drive, and the way in which the subject moves from the finish and during the recovery can be anticipated. Whilst the confidence of the predictions could be improved and validated by addressing the limitations of the study, predicted values using these models are a vast improvement than not having any and provide insight of rowing technique where there is currently none.

### 6.3 Potential outputs and application

Published literature quantifying and describing the motion of ergometer rowing has been able to demonstrate aspects of rowing technique that are influential on performance outputs, and also suggested aspects with potential influence on injury risk. However, many of the outputs of such studies are inaccessible to the majority of the rowing population, as these aspects can
be difficult to visualise, describe or for athletes to influence without quantitative measures. These measures require three-dimensional motion capture equipment, which even in a laboratory context is expensive, complex to operate and maintain and impractical for frequent use by multiple athletes. Those that do have access to such equipment have the opportunity for:

i. Instantaneous biofeedback to assist individual proprioception of changes of rowing technique, further enhanced by the access to coaches to assist in means of achieving such changes

ii. Assessment of technique with respect to known performance parameters

iii. Longitudinal monitoring of changes of technique and performance outputs

The output of rowing biomechanics research and such opportunities as biofeedback, assessment and monitoring are inaccessible to those without access to motion capture equipment. However, in this study it has been shown that instrumented measurements of a rowing ergometer have a predictive potential for measurements known to be pertinent to performance outputs. Measurements of the position and forces at the seat and handle are feasible, and are commercially available and increasingly commonly used in on-water rowing (e.g. Powerline System, Peach Innovations, Cambridge, UK).

Therefore, in quantifying the variations of forces and movements at some or all of the three points of contact the athlete interfaces with a rowing ergometer (seat, handle, feet), the opportunities listed above will be accessible without three-dimensional motion capture equipment. Such measurement systems are commercially available, robust and practical for widespread use outside of a laboratory environment. Therefore, increasing the accessibility of the outputs rowing research, improving individual performance though biofeedback, quantitative assessment and longitudinal monitoring.

A key output of this work is the opportunity to improve performance in the sport of rowing at all levels of expertise and participation, from recreational to international competition. Currently rowers on standard ergometers and on-water rowing boats can only quantifiably assess their performance outputs, such as time, speed and power output. Physiological influences of these outputs can be quantified through measurements such as specific flexibility, fitness, strength testing and anthropometric measures Nolte (2011). Measurements
can be assessed for potential improvement. However, the most significant factor of performance output is the efficiency of the athlete’s individual technique. Without motion capture equipment, the aspects of moving the body that form the rowing stroke must be subjectively assessed by coaches or individuals themselves. This subjective view must decide both what could be changed, as well as how this can or should be achieved, and then subjectively observe if the method was successful and what was achieved with respect to every aspect of the rowing stroke, not just the original desired outcome. Such a process is subject to limitations and variables, such as, with numerous others factors: access to coaches, individual proprioception, physiology, psychology and social factors.

Instrumenting an ergometer or on-water rowing boat with relatively simple kinematic measurements, combined with the predictive relationships demonstrated in this study will provide access to the output of rowing biomechanics research to more of the rowing population, i.e. opportunities to improve effectiveness of rowing technique. In addition, in quantifying aspects of rowing technique, the current subjective limitations of assessing technique are reduced. By reducing the limitation on opportunities to decide what aspects of rowing technique have scope to change, both athletes and coaches can focus on how such changes can be made. Furthermore, for those without access to coaching, these kinematic measurements and the predicted parameters calculated from them can suggest both what changes could be made, and suggest how to do so, with biofeedback allowing the individual to attempt and maintain such changes, alone. This research presents an opportunity to quantify aspects of rowing coaching, with the outcome of increasing the effectiveness of coaching and accessibility to receive it. Such opportunities would be of benefit to the GB Rowing Team that were part of this study and to recreational rowers aiming to improve efficiency and comfort rather than achieving a competitive advantage.

6.4 Observation of Seat Motion at finish of stroke

An observation during athlete testing and the descriptive analysis of the motion of the ergometer seat was that the seat would reach inflection point 1 (SI1), then as the athlete finishes the stroke with flexion of the upper limb and hip extension the seat would move in a posterior direction, reverse into anterior motion once again before the final inflection and the recovery begins. The regression models demonstrated the benefits and suggested explanation
of this motion. More anterior movement of the seat before SI1, more anterior COP at SI2, more anterior travel of the seat from SI1 to SI2 linked to a more anterior LSJ Z at knee up, a later knee up % and increased suspension suggest that the posterior movement of the seat on the recovery to indicate increased anterior pelvic rotation at the start of the recovery. Anterior translation of the seat after SI1 indicates lower levels of suspension and increases the amount of seat force applied at the finish.

Inverse dynamics methods could be used in future work to investigate the cause of this movement. Previous examples in the literature of inverse dynamic calculations of joint loading approximated the position of the ergometer seat, and thus one of the three points forces are applied to the body during when using a rowing ergometer. With the seat position measurement system created in this study, the position of the seat, if combined with kinematic measurements at the feet, seat and handle, would allow an inverse dynamics model to be created that considers the vectors of all forces applied to the body during the rowing stroke for the first time, increasing the accuracy of joint loading calculations.

6.5 Limitations of study & Technique variations

Aspects of the limitations of this study are discussed in context of a specific observation made of the athlete group and data acquired in this study.

6.5.1 Non-normal distribution of data, the effect of intensity on technique or a change of technique between steps

The inflection of the ergometer seat has been shown to vary with rate, in addition to handle timing and the timing of kinematic and kinetic variables. It is expected for kinematic measurements to vary for a multitude of reasons, such as intensity, fatigue and experience, as been demonstrated in the literature discussed in Chapter 1.

Part of preparation for regression modelling is to investigate data for normal distribution. In this process it was observed that some variables for some athletes featured a bi-modal distribution. As illustrated in Figure 6-2, some athletes demonstrate step changes in measurements during the protocol, without statistical significance related to intensity, class, body weight or gender. 2 HWW and 1 LWM exhibited a very large range of measurements. It
is proposed that different techniques are being utilised by these athletes at different points in the step test.

**Figure 6-2: Boxplot of ΔLSJ α C-MHF by athlete, within each group**

Each box represents one subject, and is comprised of their ΔLSJ α C-MHF measurements.

In the plots of the timing of the handle and seat, Figure 5-5, and the relative travel of the handle and seat, Figure 5-6, the standard deviation of measurements increased significantly with rate. Measurement error may have influenced results such as that displayed in Figure 6-2. The consistency achieved by the many of subjects tested, and normal distribution of other measurements using the same equipment, protocol and operators of equipment during the same week of testing does not rule this hypothesis out.

With respect to variation with intensity, each athlete claimed to have already performed one training session that day, before performing in this protocol. Performing multiple training and testing sessions in one day is not abnormal for elite athletes, however the individual fatigue or training load in the hours, days and weeks leading up to this testing session was not known and was not accounted for.

The influence of warm-up ergometer kinematics has been discussed by Mackenzie et al., 2008, where individuals were shown to stabilise technique after 15 minutes of intensity
equivalent to that tested in this study as R18. It is suggested that athletes should have sufficient time to prepare the body for consistent and high performance outputs. In this study, athletes were invited to row for a few minutes prior to the protocol. Some athletes chose to complete this, whilst others believed they were sufficiently prepared. Being the second training session of the day may have provided beneficial effects on both performance and proprioception as the body was warmer and more accustomed to movement, however, both warm-up and fatigue was not controlled in this study.

The intensities for each athlete undertaken in the step test protocol was suggested to be undertaken at intensities based on recent peak performance output tests for that individual, and in addition to providing data for this study, information output describing technique of the tested athletes was provided to their coaches and medical experts. The aim for these athletes was to provide data representative of their normal technique whilst producing performance outputs typical for that individual. However, this was not controlled, therefore athletes may have been performing outside of the range of performance outputs normal for that individual, and so may have changed their technique as they crossed over and under these threshold values.

When these factors are considered, alongside variations such as that displayed by certain individuals in Figure 6-2, Figure 5-5, Figure 5-6, an additional factor may be present. It is hypothesised that some athletes may use different techniques to optimise performance outputs. Discussion with an elite coach\(^4\) during the testing sessions included this observation, without referring to specific individuals in the cohort of this study. It was discussed that some athletes aim to maintain technique and change the number of strokes per minute performed to increase total work output put minute, while others use different variations of technique to produce maximum power outputs at each rate step, or between lower and higher intensities. The conscious nature of this change is unknown.

6.5.2 Future Work

Future work with a clean cohort of data would be able to account for variables such as training load, warm-up to stabilise technique, and prescribed performance outputs expected

\(^4\) Name withheld for confidentiality
for individual athletes. With sufficient sample size, athletes that maintain technique between intensity could be compared to those that appear to change technique, specifically identified not as variation, but as significant changes in kinematics exhibited between steps.

With sufficient number of subjects, an inconsistency score could be created to account for variance, both with respect to inconsistency and changes in technique between intensity steps. Studies that have considered fatigue (Pollock et al., 2012), intensity (Buckeridge, 2013, Murphy, 2009), experience level (Smoljanovic et al., 2009), gender (McGregor et al., 2008) and racing conditions (Pollock et al., 2009) investigate the contribution factors influential on rowing biomechanics. However as the potential choice of variation in this study may be a factor in an environment where maximum performance outputs are vital, not optimal movement patterns. This variation may be conscious, influenced by flexibility, or influenced by an individual's psychological response to intensity of effort, or individuals favoring different stroke rates. A study considering any of these aspects would contribute to the descriptive understanding of the rowing stroke.

The predictive modelling presented in this study demonstrated an opportunity for a greater number of the rowing population to have access to technical assessment and improvements. If the regression modelling presented in this study can be repeated with a greater number of subjects, the predictive ability of non-three dimensional measurements can be further developed. An exciting potential development would be to compare results for performance parameters and technique between ergometer and on-water rowing. It can be assessed if the same relationships exist for both, and if not, the differences in technique and performance outputs exhibited by the same athletes on the ergometer and on-water.

If the regression modelling were to be repeated and developed using a greater number of subjects, and further enhanced with factors for skill level, competitive level, age, flexibility, physiology, the predictive ability of measurements of the seat and handle could become rigorous enough to quantify aspects of rowing coaching for application by the whole rowing population. This could, through currently feasible and inexpensive technical development produce a form of ‘virtual rowing coach’, with an iterative aspect to biofeedback, suggesting technical changes and understandable cues providing a method of making these changes. Constant monitoring of measurements and adjustment of the biofeedback suggestions will allow the user to make the desired changes in a suitable manner, and maintain them. It is both
technically feasible and commercially viable to do so, as competitive rowers aim to improve performance at every opportunity, but continuous technical monitoring and development is not currently quantitatively possible, and even elite coaches cannot provide this qualitatively.

The influence of the upper body is a constant question during the analysis of the results of this work, with only broad estimations of the contribution of the upper body possible relative to the lower body. Therefore future work to include the kinematic motion of the upper limb, shoulder complex and upper spine would significantly contribute to the understanding of contributory factors of rowing technique beneficial to performance.

### 6.6 Conclusion and Application of this work

This project aimed to investigate kinematic measurements that influence performance parameters during ergometer rowing.

The results of this work indicate that predictions of kinematic measurements during ergometer rowing that would normally require direct measurement with complicated and sensitive equipment can be made using ergometer instrumentation alone. The consequences of this are that if an ergometer or rowing boat is instrumented as demonstrated in this thesis, using measurements relatively simple compared to three-dimensional motion capture equipment, flexion and extension of the lumbar spine, translation of the lumbar spine and predictions of discrete timing points of the rowing stroke can be anticipated. While the exact prediction models may over or under estimate the prediction capacity of the relationship between three-dimensional kinematic variables and those measured using an instrumented ergometer alone, this work has signposted future research, and even an approximate relationship is vastly more informative than none. If the relationships developed in this thesis are shown to apply to a wider range of the rowing population, then sensors of the same levels of accuracy and reliability, using these relationships, will be able to predict rotations and translations of the spine within 2° and 60mm respectively.

The consequence of this work is that the biofeedback systems, and understanding of the rowing stroke developed by rowing biomechanists may be able to be utilised by a wider
population of rowers, as an instrumented ergometer can provide many of the measurements which were previously only accessible to those with access to motion capture systems.
References


Chapter 7  Appendix

Appendix

7.1 Appendix A - Datasheet for Seat Position Sensor

Reflective Object Sensors
Types OPB703W, OPB704W, OPB705W

Features
- Phototransistor output
- High sensitivity
- Low cost plastic housing
- Available with lenses for dust protection and ambient light filtration

Description
The OPB703W, OPB704W and OPB705W each consist of an infrared emitting diode and an NPN silicon phototransistor mounted side-by-side on a converging optical axis in a black plastic housing. The phototransistor responds to radiation from the emitter only when a reflective object passes within its field of view. Various options allow no lens, blue polysulfone lens for dust protection or offset lens for improved resolution.

Leads are 26 AWG, PVC insulation, 4.5" (114.3mm) minimum length, stripped & tinned.

Absolute Maximum Ratings (TA = 25°C unless otherwise noted)
Storage and Operating Temperature ........................................... -40°C to +80°C
Lead Soldering Temperature [1/16 inch (1.6 mm) from case for 5 sec. with soldering iron] .......................................................... 240°C C(1)

Input Diode
Forward DC Current .............................................................. 40 mA
Reverse DC Voltage .............................................................. 2.0 V
Power Dissipation .................................................................. 100 mW(2)

Output Phototransistor
Collector-Emitter Voltage ....................................................... 30 V
Emitter-Collector Voltage ........................................................ 5.0 V
Collector DC Current .............................................................. 25 mA
Power Dissipation .................................................................. 100 mW(2)

Notes:
(1) RMA flux is recommended. Duration can be extended to 10 sec. max when flow soldering.
(2) Davato linearly 1.82 mW/°C above 25°C.
(3) d is the distance from the assembly face to the reflective surface.
(4) Lower curve is based on a calculated worst case condition rather than the conventional -2σ limit.
(5) All parameters tested using pulse technique.
(6) Crosstalk is the photocurrent measured with current to the input diode and no reflecting surface.
(7) Measured using Eastman Kodak neutral white test card with 90% diffuse reflectance as a reflecting surface. Reference: Eastman Kodak, Catalog #1257795.

DESCRIPTION

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## Types OPB703W, OPB704W, OPB705W

### Electrical Characteristics (TA = 25°C unless otherwise noted)

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<td>nA</td>
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### Combined

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<td>100</td>
<td>µA</td>
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<td>µA</td>
<td>Vce = 5 V, If = 40 mA</td>
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<td></td>
<td></td>
<td>OPB704W</td>
<td>20</td>
<td>µA</td>
<td>(9)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OPB705W</td>
<td>10</td>
<td>µA</td>
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</table>

### Typical Performance Curves

- **Reflective Surface Collector Current vs. Diode Forward Current**
- **Diffused Surface Collector Current vs. Diode Forward Current**
- **Normalized Collector Current vs. Ambient Temperature**
- **Normalized Collector Current vs. Object Distance**
- **Rise and Fall Time vs. Load Resistance**
- **Test Condition**
7.2 Appendix B – Datasheet for reflective material

**MCPET-RB**

**Furukawa – Microcellular Reflective Sheet**

**Overview**

<table>
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<tr>
<th>Property</th>
<th>Total Reflectivity</th>
<th>99</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffuse Reflectivity</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>Surface specific resistivity</td>
<td>10^12</td>
<td></td>
</tr>
<tr>
<td>Processing</td>
<td>Cutting</td>
<td>fire</td>
</tr>
<tr>
<td></td>
<td>Molding</td>
<td>molding (under special condition)</td>
</tr>
</tbody>
</table>

| Mechanical properties         | MD (MPa)           | 15  | JIS K 7667 |
| Total strength                | 15                 |    |            |
| Elongation                    | 123                |    |            |
| Tensile strength              | 15                 |    |            |
| Flaxural strength             | 15                 |    |            |
| Flaxural Modulus              | 116                |    |            |
| Electrical properties         | Q (10^12)          |    |            |
| Surface specific resistivity  | 10^12              |    |            |
| Thermal properties            | MD (MPa)           | 15  | JIS K 7667 |
| Aver. linear expansion (30-70°C) | 4.4 (10^12)     | 4.4 (10^12) |
| Thermal deformation           | MD (°C, 24h)       | -1.1 | JIS K 7667 |
| Safety                        |                      |     |
| Test item                     | Condition          | Value |
| Default value                | -                   | -     |
| High Temperature              | -60°C 1,000hrs     | 99    |
| Low Temperature               | 60°C 1,000hrs      | 99    |
| High humidity - temperature  | 50°C/95%RH 1,000hrs | 99  |
| Heat cycle test               | -30°C-80°C 500cycle | 99  |

**Sheet size**

500x1000, 600x1000, 600x1500, 600x2000, 600x2500

*All the data on this page is not guaranteed, use for reference.

Formula: ΔE = (L-1 - L-2)^2 + (a-1 - a-2)^2 + (b-1 - b-2)^2

L, a, b = default value. L1, a1, b1 = after test

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7.3 Appendix C – LabVIEW Virtual Instrument for Seat position

Note that LabVIEW is visual programming language. This ‘Virtual Instrument’ includes references to 15 inbuilt functions/scripts of LabVIEW to complete the task of determining seat position and the custom defined properties within these functions are not listed in this figure.
7.4 Appendix D – Results of Regression Analysis

7.4.1 Catch LSJ α

For dependent stroke profile variable Catch LSJ α, the data reduction and regression methodology extracted 4 variables, achieving an $R^2 = 0.794$, adjusted $R^2 = 0.767$. This accounts for 76% of the variance in the dependent variable, with a standard error of estimate of 6.0° and significant F value of 29.86 ($P<0.001$). Maximum Cook’s distance is 0.030, Mahalonobis = 3.8 and Mean Leverage is 0.11, hence individual data points had low influence on the regression model. These scores were all below limits of concern.

Residuals are plotted in Figure 7-1, with a mean of 1.48E-15 (effectively zero). Assumptions of normality, homoscedasticity and auto correlation have been satisfied. Durbin-Watson test score of 1.47, and a maximum VIF of 1.41 met non-problematic criteria levels.

![Figure 7-1: Assessment of normality and constant variance in the regression model for Catch LSJ α](image-url)
7.4.2 LSJ α MHF

With the dependent stroke profile variable MHF LSJ α, the data reduction and regression methodology extracted 3 variables, achieving an $R^2 = 0.753$, adjusted $R^2 = 0.730$. This accounts for 76% of the variance in the dependent variable with a standardised error of 6.7° and a good ability to predict with a significant F value of 29.86 (P<0.001). Maximum Cook’s distance is 0.032, Mahalonobis = 6 and Mean Leverage is 0.083, hence individual data points had low influence on the regression model. These scores were all below limits of concern.

Residuals are plotted in Figure 7-2, with a mean of $-6.01E-15$ (effectively zero). Assumptions of normality, homoscedasticity and auto correlation have been satisfied. Durbin-Watson test score of 1.35, and a maximum VIF of 2.71 met non-problematic criteria levels.

![Figure 7-2: Assessment of normality and constant variance in the regression model for MHF LSJ α](image-url)
7.4.3 Catch LSJ Z

With the dependent stroke profile variable LSJ Z catch, the data reduction and regression methodology extracted 3 variables, achieving an $R^2 = 0.856$, adjusted $R^2 = 0.842$. This accounts for 84% of the variance in the dependent variable with a standard error of 19.2 mm and a good ability to predict with a significant F value of 61.27 ($P<0.001$). Maximum Cook’s distance is 0.038, Mahalonobis = 2.94 and Mean Leverage is 0.086, hence individual data points had low influence on the regression model. These scores were all below limits of concern.

Residuals are plotted in Figure 7-3, with a mean of $1.77E-13$ (effectively zero). Assumptions of normality, homoscedasticity and auto correlation have been satisfied. Errors are suggested to be independent, and multicollinearity was not problematic from a Durbin-Watson test score of 1.65, and a maximum VIF of 1.36 respectively.

Figure 7-3: Assessment of normality and constant variance in the regression model for LSJ Z Catch
7.4.4 Finish LSJ Z

With the dependent stroke profile variable LSJ Z Finish, the data reduction and regression methodology extracted 5 variables, achieving an $R^2 = 0.856$, adjusted $R^2 = 0.828$. This accounts for 82% of the variance in the dependent variable with a standardised error of estimate of 19.0mm, and a good ability to predict with a significant F value of 30.79 ($P<0.001$). Maximum Cook’s distance is 0.038, Mahalonobis = 3.00 and Mean Leverage is 0.139, hence individual data points had low influence on the regression model. These scores were all below limits of concern.

Residuals are plotted in Figure 7-4, with a mean of -5.93E-15 (effectively zero). Assumptions of normality, homoscedasticity and auto correlation have been satisfied. Errors are suggested to be independent, and multicollinearity was not problematic from a Durbin-Watson test score of 1.98, and a maximum VIF of 2 respectively.

![Figure 7-4 Assessment of normality and constant variance in the regression model for LSJ Z Finish](image)

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7.4.5 Knee Up LSJ Z

With the dependent stroke profile variable LSJ Knee Up, the data reduction and regression methodology extracted 3 variables, achieving an $R^2 = 0.690$, adjusted $R^2 = 0.661$. This accounts for 66% of the variance in the dependent variable with a standard error of estimate of 24.1mm, and a good ability to predict with a significant F value of 61.27 (P<0.001). Maximum Cook’s distance is 0.038, Mahalonobis = 2.94 and Mean Leverage is 0.086, hence individual data points had low influence on the regression model. These scores were all below limits of concern.

Residuals are plotted in Figure 7-5, with a mean of 1.77E-13 (effectively zero). Assumptions of normality, homoscedasticity and auto correlation have been satisfied. Durbin-Watson test score of 1.10, and a maximum VIF of 1.04 respectively demonstrated no collinearity, but slight but non-problematic negative autocorrelation.

![Figure 7-5: Assessment of normality and constant variance in the regression model for LSJ Z Knee Up](image)
7.4.6 Suspension 1

With the dependent variable of Suspension 1 set, the data reduction and regression methodology extracted 5 variables, achieving an $R^2 = 0.8$, adjusted $R^2 = 0.775$. This accounts for 77% of the variance in the dependent variable with a standard error of estimate of 3.7, and a good ability to predict with a highly significant F value of 31.2 ($P<0.001$). Cook’s distance was at most 0.114, Mahalonobis 4.1 and mean leverage of 0.22. These scores were below problematic limits.

Residuals are plotted in Figure 7-6, with a mean of 9.75E-15 (effectively zero). Assumptions of normality, homoscedasticity and auto correlation have been satisfied. Errors are suggested to be independent, and multicollinearity was not present from a Durbin-Watson test score of 1.5, and a maximum VIF of 1.14 respectively.

Figure 7-6: Assessment of normality and constant variance in the regression model for Suspension 1
7.4.7 Min Seat Force

With the dependent variable of Min Seat Force/BW, the data reduction and regression methodology extracted 5 variables, achieving an $R^2 = 0.724$, adjusted $R^2 = 0.701$. This accounts for 70% of the variance in the dependent variable with a standard error of 0.1, and a good ability to predict with a highly significant F value of 43.3 ($P<0.001$). Cook’s distance was at most 0.028, Mahalonobis 1.94 and mean leverage of 0.056. These scores were below problematic limits.

Residuals are plotted in Figure 7-7, with a mean of 3.23E-17 (effectively zero). Assumptions of normality, homoscedasticity and auto correlation have been satisfied. Errors are suggested to be independent, and multicollinearity was not present from a Durbin-Watson test score of 1.81, and a maximum VIF of 1.00 respectively.

![Figure 7-7: Assessment of normality and constant variance in the regression model for Min Seat Force](image)

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7.4.8 Knee up Recovery %

For dependent stroke profile variable of Knee up recovery %, the data reduction and regression methodology extracted 5 variables, achieving an $R^2 = 0.88$, adjusted $R^2 = 0.864$. This accounts for 86% of the variance in the dependent variable, with a standard error of 1.5%, and a good ability to predict with a highly significant F value of 38.15 ($P<0.001$). Cook’s distance was at most 0.217, Mahalonobis 5.833 and mean leverage of 0.167. These scores were below problematic limits.

Residuals are plotted in Figure 7-8, with a mean of 6.7E-15 (effectively zero). Assumptions of normality, homoscedasticity and auto correlation have been satisfied. Errors are suggested to be independent, and multicollinearity was not problematic from a Durbin-Watson test score of 1.96, and a maximum VIF of 1.9 respectively.

![Figure 7-8: Assessment of normality and constant variance in the regression model for Knee Up Recovery %](image)

7.4.9 ΔPelvis° SIF to Catch

With the dependent stroke profile variable ΔPelvis° SIF to Catch, the data reduction and regression methodology extracted 3 variables, achieving an $R^2 = 0.690$, adjusted $R^2 = 0.661$. This accounts for 66% of the variance in the dependent variable, with a standard error of
estimate of 0.9°, and a good ability to predict with a significant F value of 23.777 (P<0.001). Cook’s distance was at most 0.0.176, Mahalonobis 3.00 and Mean Leverage of 0.08, hence individual data points had low influence on the regression model. These scores were all below limits of concern.

Residuals are plotted in Figure 7-9, with a mean of -3.14E16 (effectively zero). Assumptions of normality, homoscedasticity and auto correlation have been satisfied. Errors are suggested to be independent, and multicollinearity was not problematic from a Durbin-Watson test score of 1.96, and a maximum VIF of 1.41 respectively.

![Figure 7-9: Assessment of normality and constant variance in the regression model for ΔPelvis° SI2 to Catch](image)

Figure 7-9: Assessment of normality and constant variance in the regression model for ΔPelvis° SI2 to Catch
### 7.5 Appendix E – Permission Summary Table

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<td>Rowing Biomechanics Newsletter, March 2011, Volume 11 No 120</td>
<td>© 2011: Dr. Valery Kleshnev, <a href="http://www.biorow.com">www.biorow.com</a></td>
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<td>GRANATA, K. P. &amp; MARRAS, W. S. 1999. Relation between spinal load factors and the high-risk probability of occupational low-back disorder. Ergonomics, 42, 1187-1199</td>
<td>© 1999 Taylor &amp; Francis. <a href="mailto:enquiries@taylorandfrancis.com">enquiries@taylorandfrancis.com</a></td>
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