ROWING BIOMECHANICS: TECHNIQUE CHANGES WITH AN INCREASE OF POWER DEMAND

by

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A thesis submitted to the Department of Kinesiology and Health Studies
In conformity with the requirements for
the degree of Masters of Science

Queen’s University
Kingston, Ontario, Canada
(May, 2016)

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Abstract

The sport of rowing has become more popular in the past decade. While it is a relatively low impact sport, injuries can occur, specifically to the ribs (Karlson K. A., 1998) and more often in female athletes (Hickey, Fricker, & McDonald, 1997). It has been proposed that as the athlete rows, applying a cyclical load to the body, the mid trapezius fatigues and is unable to resist the force produced during the drive phase (Warden S. J., Gutschlag, Wajswelner, & Crossley, 2002). Once this happens, the scapulae are then pulled anterio-laterally which increases the compression force on the ribs, increasing the risk of injury.

The rowing motion of 12 female varsity and club rowers was tracked as they completed a fatiguing rowing test on a rowing ergometer.

Results showed that the curvature of thoracic spine changed throughout the rowing cycle but did not change with increasing power level. The transverse shoulder angle decreased (the upper back was less straight) as power level increased ($R^2=-0.69\pm19$), suggesting that the scapula moved anterio-laterally. This may be that as it tired, the mid-trapezius was unable to hold the scapulae in position. The decreasing transverse shoulder angle when the power level is increased indirectly supports the fatiguing of the retractor muscles as a mechanism of injury. It would be valuable to understand the limitations of each athlete and to be able to prescribe the optimal training zone to reduce the risk of injury.
Acknowledgements

A huge thank you to my supervisor Pat Costigan. I truly appreciate all the knowledge you have bestowed upon me during my years at Queen’s. You have been an excellent guide through this endeavor. In addition to our meetings, I always looked forward to hearing about new biomech gadgets and neat training/nutrition tidbits you had to share. With all the time I’ve spent here, I’m sure you thought you’d never get rid of me.

I would not have been able to excel during my time at Queen’s without the support of John Armitage. John, you have made such an impact on my time here that will stay with me for the rest of my life. You have inspired me in so many ways on and off the water. Your leadership and guidance has given me the opportunity to become the person I am today. I am glad you were able to be part of this process.

Thanks to Brittany McEachern, Laura Morales and Chris Welton for their incredible support and never ending excitement without which data collection would not have been as fun.

To all of my lab mates, especially those who started with me, Chris and Paul, thank you for your humor, support and understanding.

Thank you to the rowers at the Kingston Rowing Club and Queen’s Rowing Club for contributing your time to help a team mate out.

Lastly, thank you to my friends and family. Thanks to Mum, Dad, Indra and the little ones (Hi Jen and Neve!). Miriam, I couldn’t have remained as sane as I was without our daily phone call.
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Chapter 1

Introduction

With the successes of Canadian and American rowers at the 2008 and 2012 Olympics and World Championships, more and more athletes are turning to rowing for an opportunity to excel. With the formation of the Ontario Rowing Association in 2001, the sport of rowing has seen an increase from 500 rowers to over 8000 rowers as of 2014 (ROWONTARIO, 2014). This increase suggests that more and more athletes are looking for a rowing challenge.

Rowing is a seemingly simple sport, but in reality the precision and technique required to be successful must be excellent. During the drive phase of the rowing stroke, rowers experience large loads that have the potential to cause chronic injuries. Contact forces measured at the lumbar spine during the drive phase can be greater than 4000N and the contact forces in the knee have been estimated to be between 2000 and 4000N for non-experienced and experienced rowers respectively (Hase, Kaya, Zavatsky, & Halliday, 2004). The need for increased rowing speed requires the rower to produce more force in a shorter amount of time, which is measured as power.

Training workloads in rowing are prescribed using a combination of power and time. Changes in power production are prescribed regularly during training, with training zones varying between a long steady state pace (low intensity, Rowing Canada’s zone 2) and a short sprint pace (high intensity, Rowing Canada’s zone 7). With the majority of training (70-94%) taking place between low and high intensity (Rowing Canada’s zone 4) (Hartmann, Mader, & Hollmann), the athlete is at risk of becoming fatigued and, with fatigue, is unable to perform the rowing stroke with the proper technique, which predisposes them to injury (Rumball, Lebrun, Di Ciacca, & Orlando, 2005) (Clarke & Stellingwerf, 2015).
When loaded cyclically, as the body is during rowing, it is important to use proper technique to reduce the risk of injury.

The main injuries that occur in rowing are lumbar spine injuries, with an incidence of 15-25% in rowers, and rib injuries, with an incidence of 6.1-22.6% in rowers, with the higher rate for female athletes (Hickey, Fricker, & McDonald, 1997). Three mechanisms have been proposed to explain rib injuries in rowers involving three main muscle groups, including the serratus anterior, the external oblique and the mid-trapezius. The first mechanism proposes that the serratus anterior contracts so forcefully during the stroke that, over the thousands of strokes taken by the athlete, it creates a stress fracture (Karlson K., 1998) (Rumball, Lebrun, Di Ciacca, & Orlando, 2005). The contraction of the serratus anterior would not result in any visible body position changes during the drive. The second mechanism proposes a beneficial co-contraction of the serratus anterior and the external oblique to prevent the compression of the ribs. As the serratus anterior fatigues, it is no longer able to lift the ribs against the compression force of the external oblique, allowing the external oblique to compress the ribs (Karlson K. A., 1998) (Miller, Brophy, & Estenne, 1985). The manifestation of this fatigue would be exhibited by an increase in thoracic spine flexion, particularly as the athlete enters the finish of the drive. The third mechanism proposes that the mid-trapezius contracts isometrically during the drive phase to resist the force at the feet developed by the rower. When the mid-trapezius fatigues, it is no longer able to resist the foot force and the scapula slide anteriorly, changing the angle of the force vector applied to the ribs, meaning that the ribs will absorb more of this force (Warden S. J., Gutschlag, Wajswelner, & Crossley, 2002). The fatigue of the mid-trapezius would result in the shoulders becoming increasingly flexed as the mid-trapezius fails to keep the scapula retracted. These deviations from a neutral posture increase the risk for injury, while maintaining a neutral posture decreases risk (Rumball, Lebrun, Di Ciacca, & Orlando, 2005). While injuries in the lumbar spine have been explored, there has been less research observing rib injuries, especially in female athletes. One
study explored the first mechanism, the forceful contraction of the serratus anterior, as a potential mechanism of rib injury in both men and women (Vinther, Kanstrup, & Christiansen, 2006) but this mechanism was not supported as a mechanism of rib injury. Therefore, this study seeks to understand what changes in rowing technique occur that would predispose a female athlete to injury.
Chapter 2

Literature Review

During most athletic training, your muscles fatigue and the force of their contraction decreases. When this happens your muscles cannot continue to support the loads demanded by the training and so your motion starts to change (Knicker, Renshaw, Oldham, & Cairns, 2011). For example when examining a submaximal lifting task, Sparto et al. (1997) reported changes in trunk motion patterns in response to fatigue and suggested this change in technique increased the risk of spinal injury. Fatigue occurs in competitive rowers, especially when they train at during high volumes and high intensities. As they fatigue, a rower’s technique changes (Knicker, Renshaw, Oldham, & Cairns, 2011). Several studies found that poor technique and incorrect stroke mechanics play a part in developing rib, low back and extremity injuries in rowing (Rumball, Lebrun, Di Ciacca, & Orlando, 2005), (Hickey, Fricker, & McDonald, 1997), (Stallard, 1980).

The basic technique involves four important stages: the drive phase, the recovery phase and the two transition segments: blade entry and blade release (Cookson, Morrow, Nolte, & Spracklen, 2011). The drive phase, Figure 1, is characterized by a strong push on the foot plate with the legs, maintaining good body posture (a neutral spine), with straight arms and the top of the blade just under the water surface (Cookson, Morrow, Nolte, & Spracklen, 2011). When the drive phase is complete, the legs are fully extended, the shoulders are retracted, and the blade is released from the water, which should be done cleanly, minimizing water turbulence (Cookson, Morrow, Nolte, & Spracklen, 2011). Once the blade is feathered, (the face of the oar is parallel with the water), it should be carried a blade’s width above the water to prevent any drag force caused by the oar contacting the water during the recovery phase (Cookson, Morrow, Nolte, & Spracklen, 2011).
Figure 1: The drive phase, starting with the blade entry in the first photo on the left. The drive is characterized by a strong push on the legs with good back posture while the blade is buried in the water (Cookson, Morrow, Nolte, & Spracklen, 2011).

In the recovery phase, Figure 2, the rower has the opportunity to “recover” from the effort performed during the drive phase. This phase is characterized by the hands moving forward first, followed by a hinge at the hips with a neutral back as the seat starts to move forward to begin the next drive phase (Cookson, Morrow, Nolte, & Spracklen, 2011). As the end of the recovery phase approaches, the blade is squared, meaning the blade face is perpendicular to the water, in preparation to take the next stroke. The blade entry starts with a quick raise of the hands and then a strong push with the feet to secure the blade in the water (Cookson, Morrow, Nolte, & Spracklen, 2011).

Figure 2: The recovery phase, starting with the blade release in the first photo on the left (Cookson, Morrow, Nolte, & Spracklen, 2011).

The repetitive motions and cyclical loads that occur while rowing have led to chronic injuries. Over a ten year period, 172 male and female national level rowers were studied and their injuries recorded (Hickey, Fricker, & McDonald, 1997). There was a total of 320 injuries, with women
suffering 204 injuries (Hickey, Fricker, & McDonald, 1997). The majority of these injuries were overuse injuries caused by the highly cyclical nature of the sport (Hickey, Fricker, & McDonald, 1997), (Rumball, Lebrun, Di Ciacca, & Orlando, 2005). In female athletes, 27.9% of the injuries were acute, from a specific event, presenting themselves within a few days of the incident and 72.1% of the injuries being chronic, developing due to over-use over time (Hickey, Fricker, & McDonald, 1997). Rib injuries accounted for the majority of the chronic injuries, comprising 25.9% of the injuries to female athletes. The incidence of rib injury in men was lower, comprising 2.5% of chronic injuries in male athletes. Possible explanations for increased rib injury in female athletes include: possible inadequate strength and resistance training background in women (Holden & Jackson, 1985), hormonal factors that predispose women to lower bone mineral content (Galilee-Belfer & Guskiewicz, 2000) or decreased cross-sectional rib stiffness in women when compared to men (Kimpara, et al., 2003).

2.1 Models of injury

In rowers, many rib injuries occur on the anterolateral to posterolateral aspects of the ribs 5 through 9 (Karlson K., 1998). These injuries are due to high stress and overuse and occur at the ribs’ weakest point where the greatest amount of stress is concentrated (Rumball, Lebrun, Di Ciacca, & Orlando, 2005). The rib cage is loaded as a unit, and therefore direct loading on the rib is an unlikely cause of fracture. However, it has been proposed that the serratus anterior, which protracts and rotates the scapula (Kendall, McCreary, & Provance, 1983) and originates on the anterior aspect of ribs 1 to 10 and inserts on the medial border of the scapula (Cuadros, Driscoll, & Rothkopf, 1995), contracts forcefully over time to cause a stress fracture anterio-laterally at the coastal origin of the serratus anterior.
Figure 3: Anatomy of serratus anterior and external oblique muscles at the lateral rib

(Karlson K., 1998)

However, the ability of the serratus anterior to cause stress fractures has been debated, with many suggesting serratus anterior strengthening exercises to prevent injury (Warden, Gutschlag, & Wajswelner, 2002).

Another proposed mechanism for rib injury, protective co-contraction, involves the co-contraction of the serratus anterior and the external oblique (Karlson K., 1998). Since the serratus anterior lifts the ribs upwards, it protects the ribs from the compressive abdominal forces at the finish of the stroke (Warden, Gutschlag, & Wajswelner, 2002). As the serratus anterior fatigues, it is no longer able to lift the ribs to reduce the compression force generated by the external obliques. Without the positive action of the serratus anterior, the external obliques pull the rib cage downwards during the stroke (Miller, Brophy, & Estenne, 1985), (Wajswelner, Bennell, Story, & McKeenan, 2000) increasing the compression force and, therefore, compressing the ribs where the external obliques insert (ribs 5 through 12, Figure 4).
Figure 4: Potential protective effects of the serratus anterior. $F_{sa}$ is the force of the serratus anterior at its origin on the ribs. The force $F_{sa}$ is able to lift the ribs to protect from the shearing action of the external obliques (Warden, Gutschlag, & Wajswelner, 2002).

This protective co-contraction mechanism also suggests that the scapular retractor muscles are active while the serratus anterior is in use, with these muscles being used to stabilize the scapula against the rib cage (Warden, Gutschlag, & Wajswelner, 2002). However, the protective co-contraction mechanism does not explain why pain is felt in the early drive by rowers suffering from rib stress fractures (Warden, Gutschlag, & Wajswelner, 2002) suggesting that more rib loading occurs at the beginning of the drive as opposed to the finish (Warden, Gutschlag, & Wajswelner, 2002).
The muscles that retract the scapula, the mid trapezius, may also have an effect on loading. These muscles prevent the collapse of the thoracic rib cage. During the drive phase, the legs apply a large force to the foot plate. To efficiently transmit this force to the oar, the retractors must contract isometrically (Warden, Gutschlag, & Wajswelner, 2002). This contraction compresses the rib cage, as seen in Figure 5. If the retractors cannot hold the scapulae in place then the scapulae will move anteriorly (Figure 5), changing the angle at which the transmitted foot force acts on the ribs. The drive phase produces a load that may be large enough to overcome the retraction of the scapula (Warden, Gutschlag, & Wajswelner, 2002) causing the scapulae to move anteriorly and increase the compression of the rib cage. This mechanism explains the locations of the stress fractures as the altered, anterior position of the scapula lies over rib four to eight where most stress fractures occur (Warden, Gutschlag, & Wajswelner, 2002).
Figure 5: Diagram of potential compression caused by the retractors and the resistance of the oar in the drive phase. $F_{oar}$ is the estimated force of the oar on the upper limbs, $F_{retractors}$ is the force of the retractors on the scapula, while $F_{resultant}$ is the estimated resultant force of the retractors and the oar, generating a compression moment on both sides of the rib cage (Warden, Gutschlag, & Wajswelner, 2002)

2.2 Fatigue

Both central and peripheral fatigues play an important part in the training of a competitive athlete. Both types of fatigue result in reduced muscle ability (Davis & Walsh, 2009), which can manifest in result performance changes including: a decrease in cadence or velocity, an increase in rest periods, and the cessation of exercise (Knicker, Renshaw, Oldham, & Cairns, 2011). Fatigue is
also characterized by a decrease in technique execution, with tired looking, sloppy movements (Knicker, Renshaw, Oldham, & Cairns, 2011). In rowers, fatigue leads to a decrease in muscle force, stroke length and range of motion occur (Holt, Bull, Cashman, & McGregor, 2003). During the rowing stroke, lumbar spine flexion increases and the timing of maximal spine extension is delayed (Holt, Bull, Cashman, & McGregor, 2003). As a result of fatigue, poorly executed technique will predispose the athlete to injury (Rumball, Lebrun, Di Ciacca, & Orlando, 2005). Rowers will fatigue during training, especially at high training intensities. Rowing Canada describes seven zones of training intensities, where zone one is low volume, high intensity and zone seven is high volume, low intensity. These training intensities can be grouped into basic endurance, anaerobic threshold and race endurance zones (Fritsch, Nolte, Morrow, & Roaf, 2011). The following figure, Figure 6, presented by Rowing Canada at an international coaching conference (Clarke & Stellingwerf, 2015), shows the physiological benefits of training at each training level. The total adaptive impact of each training zone was evaluated based on the associated physiological benefits such as increasing the lactate threshold, increasing glycogen storage and increased cardiac output (Clarke & Stellingwerf, 2015). For our purposes, consider zones 4 through 6. The total adaptive impact of these zones are the greatest, but Figure 6 also indicates an increase in likelihood that fatigue, risk of injury and over-training may occur while training at these levels. The blue profile outlined indicates the fatigue profile, zones 4 through 6 causes the most fatigue and therefore increase the risk of injury and over-training (Clarke & Stellingwerf, 2015).
Figure 6: Fatigue profile, risk of injury and over-training in relation to varying zones of training. Figure adapted from Rowing Canada (Clarke & Stellingwerf, 2015)

Table 1 taken from a coaching development program course for level three coaches taught by FISA, the international rowing federation (Hartmann, Mader, & Hollmann), shows the typical percent of time training spent at the various intensity zones. This includes all cross-training as well as rowing specific training. At any given time of the competitive year the amount of time training in zone 4 is above 70% (Hartmann, Mader, & Hollmann). Based on Figure 6, the athlete is placing themselves at an increased risk of injury, overtraining and fatigue (Clarke & Stellingwerf, 2015) although they are reaping the most benefits from their training (including cross-training and rowing specific training).
Table 1: Presentation of the analysis of training data in accordance with the different intensity zones. Adapted from (Hartmann, Mader, & Hollmann)

<table>
<thead>
<tr>
<th>Training Period</th>
<th>Zones (% of the total amount of training)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IV</td>
</tr>
<tr>
<td>Preparation period</td>
<td></td>
</tr>
<tr>
<td>Autumn/winter</td>
<td>90-94</td>
</tr>
<tr>
<td>Winter/spring</td>
<td>86-88</td>
</tr>
<tr>
<td>Competition period</td>
<td>70-77</td>
</tr>
</tbody>
</table>

2.3 Training and selection

An estimate of the athlete’s training effort is based on their time to row 500m – the lower the time required, the higher the training intensity. The time to row 6k is used to determine/calculate the rower’s 500m time for each training zone. The Rowing Canada Aviron coaching association recommends that rowers maintain their 500m time as outlined in Table 2. This would be their 500m time for their 6k test plus the additional time.

Table 2: Zones of training intensity according to Rowing Canada. Adapted from Rowing Canada (Rowing Canada Aviron and Coaching Association of Canada, 2013)

<table>
<thead>
<tr>
<th>Zone</th>
<th>500 meter split</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>6k +13 seconds</td>
</tr>
<tr>
<td>3</td>
<td>6k + 7 seconds</td>
</tr>
<tr>
<td>4</td>
<td>6k + 2 seconds</td>
</tr>
<tr>
<td>5</td>
<td>6k - 2 seconds</td>
</tr>
<tr>
<td>6</td>
<td>6k- 7 seconds</td>
</tr>
<tr>
<td>7</td>
<td>OPEN</td>
</tr>
</tbody>
</table>
During the winter months, a rowing ergometer can be used to train since it mimics the basic rowing motion (Lamb, 1989). The ergometer has been used by Rowing Canada Aviron to conduct standard rowing tests, such as the 6000m, 2000m and lactate test (ramp test format), to select its top Canadian rowers (Rowing Canada Aviron, 2014).

A fatiguing ramp test is a common test used to evaluate an athlete’s cardiorespiratory function (Buchfuhrer, Hansen, Robinson, Sue, Wasserman, & Whipp, 1983). The idea behind a ramp test is to increase exercise difficulty until the participant fatigues to the point that they can no longer complete the exercise, inducing fatigue to the point of task failure. The test can be completed on a bike or treadmill, but it is conducted on rowing ergometers by Rowing Canada. It is recommended that the participants reach task failure within 8-12 minutes (American College of Sports Medicine, 2000) and that the protocol have small and frequent increases in workload (Myers & Bellin, 2000). A sample ramp protocol would include levels representing a 25W increase in power for every 2 minute level (Myers & Bellin, 2000) or increments of 15, 30 or 60 W per 2 minute (Buchfuhrer, Hansen, Robinson, Sue, Wasserman, & Whipp, 1983). The termination of a ramp test would therefore indicate that the athlete has fatigued to task failure and is no longer able to continue at the specified power level.

2.4 Purpose

The purpose of this study was to identify changes in rowing technique during a ramp test.

2.4.1 Objectives

The following objectives were identified:

1) To measure upper body posture (technique) during a ramp test.
2) To ascertain if technique changes matched potential injury mechanisms.
3) To develop recommendations for training that may reduce injury risk.
Chapter 3

Methods

3.1 Participants
Participants were recruited from the Queen’s Varsity Rowing team as well as club athletes from the Kingston Rowing club. All rowers competing for their respective club during the season of the study were eligible. From the available athletes, fourteen agreed to participate in the study. Data was collected from 14 female rowers; however two participants were removed from this study due to missing three-dimensional data. The remaining 12 participants had an average height and weight of 174.8±5.2cm and 69.6±7.9kg respectively. The average 2km score for the group was 7:39±22.0 seconds and they had been rowing for an average of 3.8±2.0 years. Within this group of athletes, many were or had been injured but continued to perform at their highest level. Injuries within this group included: 2 incidences of rib injuries (one current, one recovered), 2 incidences of forearm tendinitis, 3 incidences of lumbar spine (one current, two recovered), tibia fracture, 2 foot fractures, 2 incidences of knee pain.

3.2 Instrumentation
The Qualisys motion capture system collected 3D motion data at a rate of 200Hz. The Concept 2 ergometer, supplied by the Queen’s rowing team, was instrumented with a load cell which was added to the ergometer’s chain to measure the force on the chain (Figure 7). The load cell data was collected simultaneously with the motion data at a rate of 200Hz.
Figure 7: The load cell used to measure the ergometer’s handle force.

To calibrate the load cell, it was suspended and loaded using weights of known mass. The weights were added to the load cell in random order and the voltage was recorded at each weight interval. There was a linear relationship between voltage recorded by the load cell and applied load (Equation 1).

\[
\text{Force} = 312.77 \times V - 450.04, \quad R^2 = 0.99
\]  

Equation 1: Calibration equation for the load cell used to find force from voltage, where V is in volts and Force is the force in Newtons.

Figure 8 shows the instrumented ergometer and the orientation of the lab space. The ergometer was placed in the lab space such that the y-axis was parallel to the long side of the ergometer, the x-axis parallel to the short side of the ergometer and the z-axis perpendicular to both.
A total of 82 10mm reflective markers were used to capture the rower’s body movement. On the axial skeleton, markers were placed on the seventh cervical vertebrae and the suprasternal notch. To identify the seventh cervical vertebrae, a flexion-extension method was used to identify the lowest moving cervical vertebra as the sixth cervical vertebra (Shin, Yoon, & Yoon, 2011). The seventh cervical vertebra was then identified as the next immobile vertebra. To define the spine, markers were placed on T1, T4, T7, T10 and T12. The first thoracic vertebra was identified as the vertebra following the seventh cervical vertebra, with the remaining vertebra identified by palpation based on the location of the seventh cervical vertebra. On the appendicular skeleton, all of the markers were placed bilaterally. On the shoulder and arm, markers were placed on the acromion, the lateral and medial epicondyles of the elbow and the styloid processes of the radius and ulna. To identify the acromion, the participant was asked to raise their arm while the flat region of the acromion was located at the origin of the deltid (Karduna, McClure, Michener, &
Sennett, 2000). If this marker were to be placed either more anterior or posterior to this flat area, there would be a bias in any angular calculation using this marker. To reduce the influence of any potential bias only the relative change in angles was used rather than absolute orientation. Clusters of four markers were also placed on the humerus at the midpoint between the medial deltoid and the lateral epicondyle of the elbow as well as on the forearm at the midpoint between the lateral epicondyle of the elbow and the radial styloid process. To track the movement of the ergometer handle, a single marker was placed on the handle and on the ergometer’s handle frame.

Figure 9: An athlete with full marker sets, showing where the markers were placed on the rower to collect spinal and acromial motion.

3.3 Protocol
The protocol was approved by the Queen’s General Research Ethics Board (Appendix A). Each athlete read the letter of information and signed a letter of informed consent. The participants
were asked a series of questions concerning their physical performance and health (Appendix B). Information such as their latest 2000m ergometer time, 6000m ergometer time were requested as well as their height, weight, gender, age and years of experience. This form also recorded the injuries sustained throughout their rowing careers and their current injuries.

The ergometer drag factor was set to 110, which is the recommended setting for both lightweight and open female participants (Rowing Canada Aviron, 2013).

The rowers adjusted the height of the footplate to match their use in a regular training session. Each participant warmed up for 20 minutes before performing any high exertion work.

The test was a ramp test. For each test interval, the rower was asked to pull a consistent wattage for 2 minutes and at each new interval the wattage was increased. The wattage started at 100 watts and increased by 20 watts test interval until the rower could no longer maintain the wattage. There was no cadence restriction during the intervals, as long as the rower was able to maintain the desired wattage with an error of plus or minus 5 watts they were permitted to continue the test. The rower was asked to stop rowing if they were unable to maintain the desired wattage for three consecutive strokes. This was determined visually. The test could also be terminated if the rower ceased activity voluntarily.

### 3.4 Data Analysis

All of the marker data and force data collected was exported as .mat files and analyzed using Matlab (Natick, MA) (Appendix C).

Any missing marker data was filled by interpolating between the data immediately before and after the missing data (Appendix C). The marker data was filtered using a butterworth filter with a 6Hz cutoff frequency. This filter was appropriate as it was used in previous studies observing rowing (Vinther, Kanstrup, & Christiansen, 2006). The filtered marker data was segmented into strokes. To determine the catch and finish positions, the peaks of the ergometer handle movement in the y-axis were used (Appendix C). The catch and finish positions were defined as the maximal
and minimal distance in the y-axis, respectively. Using the position of the catch and finish times, all of the marker data and the force data was segmented into individual strokes. The calibration equation was applied to the load cell data. All data was time normalized to 101 data points so that the timing of the stroke could be represented as a percentage of the stroke (Appendix C).

3.5 Outcome Measures
The primary outcome measures were the transverse shoulder angle and the thoracic spine angle. The transverse shoulder angle and thoracic spine angle were calculated at each time point for each stroke and for every stroke throughout the ramp test using the positional information from the body mounted markers. Secondary outcome measures included measures of power, hand force and rowing cadence. The measured power was computed for each strike as the summed hand force times the net displacement of the handle divided by the time for the stroke. The hand force was measured continuously throughout the stroke by the load cell attached to the ergometer’s chain. The cadence was calculated as the inverse of the time taken to row the stroke.

3.5.1 Transverse shoulder angle
The transverse shoulder angle is described as the angle from between the left acromion, the top of the thoracic spine (T1) and right acromion. Two vectors were formed, one from T1 to the right acromion and a second from T1 marker from the left acromion (Figure 10). The transverse shoulder angle was the dot product of these two vectors. Any movement of the acromion indicates a change in scapular position. It was assumed that the majority of the acromion’s movement was in the transverse plane.
3.5.2 Thoracic spine angle

The thoracic spine was defined as that section of the spine between the 12th thoracic vertebrae and the first lumbar vertebrae (Gajdosik, Albert, & Mitman, 1994). To calculate the thoracic spine angle, its radius of curvature was found using the data of the T1, T4, T7, T10 and T12 markers. Any error due to skin movement is avoided by estimating the radius of curvature, which does not require absolute marker position but only requires that the markers remain aligned with the thoracic spine. It is assumed that the athletes motion is in the y-z plane.

Figure 10: Two vectors between T1 and right and left acromion in the T1-T4 plane.
The radius of curvature was calculated in the y-z plane (side view). To accomplish this, the five thoracic spinal markers were fitted to a circle in 2D space. To fit the data points, the mean position of the y-position and x-position values were found. The difference from the mean position for each data point was calculated and from the difference of the mean the variances were calculated.

\[
\bar{Y} = \frac{\sum_{i=1}^{n} Y_i}{n}
\]  

(2)

Equation 2: The mean of the y-position of a single marker, where Y is the position value and n is the number of data samples for the marker.
mean_{diff} = \frac{\sum_{i=1}^{n}(Y_i - \bar{Y})}{n} \tag{3}

Equation 3: The mean difference of the position data, where \( Y_i \) is the individual marker position, \( \bar{Y} \) is the mean position value and \( n \) is the number of data samples for the marker.

var_{mean} = \frac{\sum_{i=1}^{n}(mean_{diff_i})^2}{n} \tag{4}

Equation 4: The variance of the position data, where \( mean_{diff} \) is the mean difference of the position data and \( n \) is the number of markers.

Least mean squares method was used to find the best fit of the thoracic spinal data points.

\[
    t = \frac{mean_{diff_Y}}{(mean_{diff_Z}^2 + var_{mean_Z} + mean_{diff_Y}^2 + var_{mean_Y})/2} \tag{5}
\]

Equation 5: Least squares solution to fit the radius of the curve. Where \( t \) is the least squares solution, \( mean_{diff_Y} \) is difference in Y position from the mean Y position, \( mean_{diff_Z} \) is the difference in Z position from the mean Z position and \( var_{mean_Z} \) is the variance of the Z position data and \( var_{mean_X} \) is the variance in the X position data.

The radius of curvature was then calculated.

\[
    radius = \sqrt{var_{mean_Z} + var_{mean_Y} + t(1)^2 + t(2)^2} \tag{6}
\]

Equation 6: This equation was used to find the radius of curvature (Appendix C). Radius is the radius of the fitted circle, \( var_{mean} \) is the variance of the difference of the mean, and \( t \) is the least squares solution to fit the thoracic curvature.
To be able to visualize the effect of the radius of curvature, the estimated angle of the thoracic spine was found. This was done by finding the midpoint of the curve calculated using the radius of curvature and the z position of T1 and T12 markers (the upper most and bottom most extents of the thoracic spinal markers). The midpoint in the z-axis was calculated by taking the mean of the T1 and T12 z-positions. Since the y-position of the data points might not fall on the calculated curve, the z-position values were plugged into the calculated equation of the circle and the roots of the quadratic equation were found. The solutions to the quadratic equations were the y-position values associated with the z-position values of T1, T12 and the midpoint. Using these new yz coordinate pairs, two vectors were created. The first vector was from the midpoint of the thoracic spine to T1 while the second vector was from the midpoint to T12. The dot product of these two vectors was the angle of thoracic spinal flexion.

Figure 12: Sample thoracic spine markers with two vectors shown between T12 and midpoint and T1 and midpoint.
3.5.3 Measured power

To calculate measured power, the following equation was used:

\[
Power = \sum_{i=1}^{n} F_n \times \frac{d}{t}
\]  

Equation 7: Equation to calculate power, where \( F \) is the force at the handle summed for each data point, \( n \), \( d \) is the distance covered by the handle and \( t \) is the time to complete a stroke including drive and recovery time.

3.5.4 Cadence

Stroke cadence was calculated using the time to complete a full stroke. The time per stroke was manipulated to find strokes per minute as shown in the following equation.

\[
Cadence = \frac{60}{time \ (mins) \ per \ stroke}
\]  

Equation 8: Equation used to calculate cadence of the athlete. Time per stroke was the time from one catch to the next measured in seconds. Cadence is the number of strokes performed in one minute.

3.6 Statistical analysis

Principal components analysis is a statistical technique that separates data into a series of principal components explaining variance in the data. The first component explains the most variance while the last component explains the least. In performing principal components analysis on curve data, the mean curve is subtracted from curves across each dimension (y and z directions). What is left is the mean adjusted data. Principal components analysis computes the covariance matrix for the matrix of mean adjusted data. From this covariance matrix, the eigenvectors (scores) and eigenvalues (weights) of this matrix are found. The scores represent a vector along which variance in the data is best explained. The weights determine which score represents the most variance in the data. The greater the weight, the more variance is explained by
its associated score. Therefore, if the variable is highly correlated to the score, it most likely related to the variance in the data.

In this study, principal components analysis was run on the transverse shoulder angle and thoracic spine angle curves for the drive phase for each athlete individually. Five strokes per power level were used for each athlete. A principal components analysis was then conducted for each athlete. The first principal component score was plotted against multiple variables to find which variable explained the most variance.
Chapter 4

Results

As the athlete progressed through the incremental ramp test their cadence increased, as expected. Additionally, the thoracic spine angle did not change and the transverse shoulder angle increased in flexion. Figure 13 shows that during the first target power level, 120 watts, the cadence was low, at an average of 20.2±1.3 strokes per minute. This cadence was expected for lower power outputs. As the target power level increased during the test the cadence increased linearly. At the maximal target power level (260 watts) the cadence was 28.4±0.3 strokes per minute. The power level and cadence were strongly correlated with a Pearson R-squared value of 0.97. Not all athletes were able to reach the higher power levels and, as a result, the number of participants for each power level varied.

Table 3: Mean (SD) of number of participants (N), measured power and cadence at each target power level.

<table>
<thead>
<tr>
<th>Target Power (Watts)</th>
<th>N</th>
<th>Measured Power (Watts)</th>
<th>Cadence (strokes/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>12</td>
<td>120 (20)</td>
<td>19.8 (1.6)</td>
</tr>
<tr>
<td>140</td>
<td>12</td>
<td>143 (13)</td>
<td>21.0 (1.3)</td>
</tr>
<tr>
<td>160</td>
<td>12</td>
<td>167 (15)</td>
<td>22.3 (1.6)</td>
</tr>
<tr>
<td>180</td>
<td>12</td>
<td>183 (11)</td>
<td>25.3 (1.4)</td>
</tr>
<tr>
<td>200</td>
<td>11</td>
<td>204 (13)</td>
<td>24.4 (1.6)</td>
</tr>
<tr>
<td>220</td>
<td>7</td>
<td>228 (5.4)</td>
<td>26.3 (1.2)</td>
</tr>
<tr>
<td>240</td>
<td>5</td>
<td>247 (3.7)</td>
<td>27.2 (3.3)</td>
</tr>
<tr>
<td>260</td>
<td>2</td>
<td>264 (1.6)</td>
<td>28.3 (0.3)</td>
</tr>
</tbody>
</table>
Figure 13: Cadence at each power level with associated standard deviation. As the power level increases, the cadence increases as well.
Figure 14 shows that the force exerted on the handle increased as the power level increased. The force values for power levels 120 watts to 180 watts gradually increased, where force values for power levels 200 watts to 260 watts remained fairly stable around 654.9±13.0N. The first approximately 20% of the drive phase did not register any force at the hands, even though the handle was moving. This could be due to slack in the ergometer chain, which did not catch the wheel until 20% through the drive phase. The force recorded at the hands at the finish was defined as zero as this is where the athlete had changed the direction of their movement, starting the recovery phase of the stroke.
Figure 14: Average force at the hands in Newtons for the group of rowers during the drive phase. Each colored line indicates a different power level, ranging from 120 watts to 260 watts. The maximum force achieved at each level is distinct until 200 watts, where the power levels are seen to cluster around 653.9±13.0N.

Figure 15 shows that thoracic flexion was constant during the first 40% of the drive phase. The rowers’ thoracic spinal angle was less flexed as they picked up the load at the catch and were able to maintain a straighter thoracic spine until approximately 40% through the drive phase. The rowers’ thoracic spines became more flexed as they moved into the finish position. There was no consistent change in spinal flexion as the target power level increased. For instance, when pulling at 240 watts the average spine angle was less flexed than when pulling at 120 watts.
Figure 15: Average spine angle in degrees as a drive sequence was completed. Each colored line is a different power level, ranging from 120 watts to 260 watts. The spine angle is seen to vary depending on power level and does not have a linear relationship with power level.

Principal component analysis was performed by participant and these were superimposed into grouped results. The group results are presented. The principal components analysis conducted on the thoracic spinal curves showed that the first principal component explained, on average, 82.0±15.5% of the variance. However, there was no relationship between power level and first principal component score (Figure 16).
Figure 16: The first principal component score of the thoracic spine of all rowers for all levels as a function of power level. There is no relationship between the thoracic spinal curve and power level.

The transverse shoulder angle also changed through the drive phase (Figure 17). From the catch to the end of the drive phase the acromions moved posteriorly, indicating scapular retraction, which was seen as an increase in the transverse shoulder flexion angle (i.e. the upper back is less flexed). The force profile (recall Figure 14) of the drive phase showed that the force at the hands decreased during the second half of the drive phase which may have allowed the athletes to straighten their shoulders against a reducing load. However, as the ramp fatigue test continued the rowers delayed the time at which they began straightening their upper backs even though the force profile is similar to that at the lower target power levels. For example, an average transverse shoulder flexion angle of 150 degrees is reached at less than 70% of the drive phase at a target
power level of 120 watts while at a target level of 240 watts this same angle is not reached until after 80% of the drive phase.

The principal components analysis conducted on the transverse shoulder angle curves, again individually and then grouped, showed that the first principal component explained, on average,
71.0±12.5% of the variance. Unlike the thoracic spine angle, this first principal component score did vary with power level. (average Pearson r² of -0.69±0.19). The correlations ranged from -0.25 to -0.92.

Figure 18: The first principal component score of the transverse shoulder angle of all rowers for all levels as a function of power level. There is a negative correlation between the PCA score and the power level, where a lower PCA score means a more flexed transverse shoulder angle.

In Figure 19 the majority of the variance in the first principal component is in the first 80% of the drive. The most variance occurs at the catch position where athletes vary their body position as they begin power production. Variance only decreased as the athletes started to enter the end of the drive phase.
Figure 19: The mean adjusted data for the first principal component showing that the most variance occurs at the catch position, with variance continuing to 80% of the drive phase, with the least amount of variance at the finish.

Since this principal component captures variation in the transverse shoulder angle within the first 80% of the drive phase, the PCA scores associated with each curve reflected the variation in the first 80% of the drive phase. The curves for two rowers, one with a high PCA score and another with a low PCA score scores were plotted to help understand what the scores mean (Figure 20).
When comparing the positive and negative scores it is clear that for the negative score the transverse shoulder angle at the catch is low and remains low during the drive phase. The positive score shows that the transverse shoulder angle at the catch was larger; the shoulders were less flexed and remain less flexed throughout the drive phase. Therefore, a lower score on this principal component indicates a more flexed transverse shoulder angle at the start of the drive phase.

The results presented above are indicative of the average rowing performance but not all rowers responded the same way. To explore the range of individual responses three different cases were
explored. The first case, F11D, was chosen because this athlete was not affected by power. She represents an athlete whose posture did not seem to be affected by an increase in power. F11D, did not show any relationship between power level and transverse shoulder angle (Figure 21), meaning that the increase in power level did not affect the athlete’s shoulder angle during the fatigue test. The scores appear to be distributed at random, suggesting that while this athlete’s transverse shoulder angle changed during the fatigue ramp test, it did not change with respect to increasing power level.

![Figure 21: F11D, first principal component scores for the transverse shoulder angles of participant F11D with associated measured power level.](image)

The second case, D01C, was chosen because she is an experienced rower with a 2k time of under 7:10 minutes who was injured during the season but continued to compete. D01C has a strong
negative relationship (Figure 22) between her transverse shoulder angle and power. Many athletes have a similar relationship. This may indicate that the other athletes who exhibit this trend, while not currently injured, could become injured if they continue this pattern. For this athlete, D01C, the first two power levels (120-140 watts) were characterized by variable transverse shoulder angle PCA scores. The following six power levels demonstrated a negative relationship between the score and power.

![Graph showing the relationship between first principal component transverse shoulder angle score and power level, with R² = -0.91.](image)

**Figure 22:** D01C, relationship between first principal component transverse shoulder angle score showing decrease in score with increase in power level.

The third case, D25Y, was chosen because she had suffered from rib injuries and has sought treatment. She was the only rower who exhibited the pattern shown in Figure 23. She was able to maintain a stable transverse shoulder angle for the first 7 power levels before reaching a power output level where her transverse shoulder angle score suddenly decreases. She has reached high
levels of competition and her 2k time is under 7:10 minutes. In Figure 23, her transverse shoulder angle score is positive for the first 7 power levels. Once she reaches 240 watts, her transverse shoulder angle score suddenly decreases.

![Graph showing relationship between first principal component shoulder score and power level](image)

Figure 23: D25Y, relationship between first principal component shoulder score showing a decrease in the transverse shoulder angle PCA score with an increase in power level, once a threshold of 240 watts has been reached.

The transverse shoulder angles for D25Y are shown in Figure 24. The first 6 power levels are clustered together, while the last two power levels, 240 watts and 260 watts, are distinguished from the group.
Figure 24: D25Y, transverse shoulder angle as a function of percent drive phase. Each colored line indicates a power level. It should be noted that as the power level increases, the participant’s transverse shoulder angle becomes more flexed.
Chapter 5

Discussion

An important technique change, the increased flexion of the shoulders, occurred during the incremental ergometer test. The transverse shoulder angle changes throughout the drive phase, being more flexed at the catch and more flexed with increasing power level. During the drive phase (Figure 17) the transverse shoulder angle at the catch was flexed. Through the majority of the drive, the flexion is maintained, until the peak force has been achieved (near 60% of the drive phase) and the force starts to decrease. Then the transverse shoulder angle becomes less flexed and the scapula were retracted with the rower finishing the stroke with a transverse shoulder angle above 170 degrees. Starting at the fifth increment step, there is a delay in the athlete’s ability to retract their scapula. Instead of retracting their scapula right after the peak force occurs, the athletes only start to retract their scapula at around 75% of the drive phase. This could be caused by fatigue during the ramp test. The mid-trapezius could be fatigued and unable to resist the force developed at the hands, allowing the handle to pull the scapula anterio-laterally during the drive phase. Transverse shoulder extension may not be able to begin until the force decreases enough such that the athlete can retract their shoulder blades.

The transverse shoulder flexion angle represents the acomion’s position and acromion position as there is a link between transverse shoulder flexion and scapular position. This helps interpret the transverse shoulder flexion angle as it relates to compressive force on the ribcage. A more flexed transverse shoulder angle (especially at the catch), indicates that the scapulae have moved increasingly in the anterio-lateral direction. With the scapulae shifted forward there is a larger force component in the medio-lateral direction being applied to ribs 4 through 9. A less flexed transverse shoulder angle indicates that the scapula were more retracted by the mid-trapezius and that the angle of the rib compression force is less medio-
lateral and more anterior-posterior, which reduces the medial compressive force on ribs 4 through 9.

The thoracic spine angle did not change as a consequence of power level. However, the thoracic spine became more flexed (Figure 15) as the drive phase progressed. At the catch, the athletes’ thoracic spines were minimally flexed and started to flex at approximately 40% of the drive phase. The increased thoracic flexion could be due to the increasing load (Figure 14) which the rower develops during the drive and peaks at 60% of the drive phase. However, after the load peaked and began to drop, the thoracic spine continued to flex. This is curious because it would seem that the athlete would be able to extend their thoracic spine as the force begins to reduce. At the finish, the external obliques are most active (Rumball, Lebrun, Di Ciaccia, & Orlando, 2005) and it could be that they are acting to increase the flexion of the thoracic spine. It could also be that the rower is attempting to lengthen their stroke and by increasing the flexion of their thoracic spine by allowing their thoracic spine to collapse over their knees when they are at the catch. They are able to increase the distance covered, but sacrificing their posture in the process.

The reported peak force and power produced by women rowers are in line with those reported by others. Kane et al. (2012) reported that 7 female club level rowers who, when they maintained the same cadence as the athletes in the current study, 27.8±0.6 compared to 28.4±0.3 strokes per minute respectively, achieved a power output of 187.0±13.2 W (Kane, MacKenzie, Jensen, & Watts, 2012). These athletes were described as non-elite, but conditioned club rowers (Kane, MacKenzie, Jensen, & Watts, 2012). British national team athletes maintained a stroke rate of 28.4±1.50 strokes per minute and produced 351.9±35W of power (McGregor, Patankar, & Bull, 2008). The participants in this study produced power outputs of 264±1.64 W which is between the club level athlete and the national level athlete, which was expected and suggests that the power recorded at the hands during this study was reasonable.
5.1.1 Supporting an injury mechanism

The relationship between power level and transverse shoulder angle indirectly support the fatiguing of the scapular retractors as a mechanism of injury. As the athlete increased their power output, the transverse shoulder angle PCA score decreased, indicating that the transverse shoulder angle became more flexed; the scapula moved anterio-laterally as the power level increased. This suggests that the retractors of the scapula are unable to support the increased load at the increased power levels. A more anterio-lateral position of the scapula applies increased compression force to the ribs medio-laterally, coinciding with the typical location of the rib stress fractures (Warden, Gutschlag, & Wajswelner, 2002).

The shearing effects of the serratus anterior as an injury mechanism do not seem to agree with the results of this study. The shearing effect mechanism would suggest that as the serratus anterior contracts it does so forcefully enough to cause a shearing force on the ribs and with enough repetition to eventually cause a stress fracture. However, the serratus anterior is active mainly at the finish of the rowing stroke and during the recovery phase, when the force at the hands is low (Warden, Gutschlag, & Wajswelner, 2002). During the finish, the serratus anterior activates to resist the force developed at the hands, lifting the ribs upwards. Since this force at the hands is low at the finish, the resistance to the serratus anterior’s protraction of the scapula would be limited, reducing the shearing force of the serratus anterior that could cause damage to the ribs (Warden, Gutschlag, & Wajswelner, 2002).

The second explored injury mechanism, the protective effect of the serratus anterior, was not supported by this study. In order for the serratus anterior to be protective it requires the co-contraction of the external obliques and the serratus anterior. Once the serratus anterior fatigues, or there is an imbalance between the external obliques and the serratus anterior, the injury mechanism comes into play. The external obliques are mainly activated when the rowers are at the end of the drive phase (Warden, Gutschlag, & Wajswelner, 2002). The effect of the external oblique overpowering the serratus anterior may have occurred as the athletes entered the finish of
the drive phase. When the external oblique overpowers the serratus anterior, the serratus anterior has fatigued and can no longer resist the pull of the external obliques on rib 4-9 and is therefore unable to lift the ribs and resist the compression force of the external oblique. However, this effect did not change with an increase in power level. The athletes had increased thoracic flexion as they entered the finish, suggesting that there was an imbalance in the co-contraction of the external obliques and the serratus anterior. This could be due to a pervasive strength imbalance, but does not suggest that the serratus anterior has fatigued over the ramp test. There was no notable change in the thoracic spinal flexion with an increase in power over the period of the ramp test. This protective mechanism of the serratus anterior however was not supported by this study.

5.1.2 Exploring the cases
The first case, F11D, does not change her transverse shoulder angle score as the power level increases (Figure 21). This athlete has suffered from many injuries while racing for her respective club including a low back injury. It could be that instead of sacrificing her thoracic posture, she is instead compensating by increasing flexion in her low back (a portion of the spine we did not measure). Furthermore, F11D’s maximal 2k time was 8:00 minutes and was not able to develop as much power as some of the other athletes, only reaching 180 watts on the ramp test. Her mid-trapezius may have been able to resist the force developed at the hands during the drive phase for these lower power levels. If she had continued the ramp test she may have started to increase her transverse shoulder flexion as the power levels increased and/or as she fatigued.

When performing such cyclical work, any change in posture could be considered negative. Sparto et al. (1997) observed the posture and coordination during a repeated lift, similar to that performed during the rowing stroke, the ability to maintain a posture decreased over the time as repeated lifts were performed (Sparto, Parnianpour, Reinsel, & Simon, 1997). This decreased postural stability may increase the risk of injury (Sparto, Parnianpour, Reinsel, &
Simon, 1997). With this in mind, the same can be said for the sport of rowing. The rower is applying a load to their body and as they continue to row, their posture (transverse shoulder angle) changes. If the postural stability of the athlete cannot be maintained, they place themselves at increased risk for spinal injury. Therefore, any change in posture can be considered an increased risk for injury.

Two of the cases, D01C and D25Y, exhibited a negative relationship between transverse shoulder angle and increasing power level. However, one was able to maintain postural stability for longer than the other. Both athletes pull comparable ergometer 2km scores, both between 7 mins and 7:10. They have both suffered from rib injuries in their upper ribs, between rib 9 and 4. One athlete (D25Y) has stopped receiving treatment and no longer feels pain while rowing. The other (D01C) is continuing to seek treatment for her injury. When their transverse shoulder angle PCA scores were observed (D25Y described in Figure 22 and D01C described in Figure 23), there are distinct trends that could help explain why one athlete continues to be injured while the other athlete is able to maintain her training load. The PCA scores for D25Y remain high for the majority of the ramp test suggesting that she is able to maintain postural stability, until approximately 240 watts, where there is a decrease is her transverse shoulder angle score. She is able to keep her scapula more retracted, until 240 watts. When fully exerting herself in a 2k race, the athlete is able to maintain 296.4 watts of power on average, which means that the athlete can maintain proper technique at up to 80% of her maximal effort. Since much of her training happens below 80% of her maximum, this athlete can maintain proper technique for much of her training, which may reduce her rib injury risk.

While D01C is capable of exerting herself to a similar extent as D25Y, she shows a different transverse shoulder angle to power relationship than D25Y. During the first few power levels, seen in Figure 22, D01C seems to have inconsistent shoulder angle scores. The first two power levels, 120 watts and 140 watts, are not very challenging for this athlete, with her Rowing
Canada predicted steady state training (zone 3) being approximately 170 watts, based on her reported 6k score and the recommended training zone in Table 2. She has trouble maintaining a consistent posture during the two first power levels (120-140 watts). Once D01C reaches her steady state pace the athlete has a consistent decrease in transverse shoulder angle with an increase in power output. Unlike D25Y, D01C starts to see a decrease in her transverse shoulder angle at 61% of her maximal exertion. Therefore, D10C trains more often with improper technique, which puts her at a higher risk for rib injuries.

Since increasing the stroke distance handle covered by the athlete increases their power output, the athletes are encouraged to reach further as they enter the catch position. To maximize their reach, the athlete must have good flexibility in their ankles and hips to be able to keep their heels on the footplate and to minimize the space between their heels and hips as they approach the catch. If this is done properly, the athlete will maintain a strong body position, with their shoulders retracted and their spine neutral. If the athlete does not have good flexibility, they will not able to compress their hips to their heels while keeping their heels on the foot plate. To accommodate for their lack of flexibility, the athlete may increase their reach by curving their upper back and moving their scapula anterio-laterally to gain that extra distance. This might increase the risk of upper back injuries. It is also possible that the athlete may attempt to gain this extra distance by increasing the flexion of the lumbar spine without sacrificing their upper thoracic posture. This might increase the risk of lower back injuries, as large forces and moments act at the low back, with compression forces of approximately 4.6 times the athlete’s weight (Morris, Smith, & Payne, 2000) and moments of 300Nm (Hase, Kaya, Zavatsky, & Halliday, 2004).

It is very difficult to track scapular motion because of the skin artifact that occurs as the skin slides over the scapula during dynamic movement. There have been a few different techniques used to estimate scapular motion. One of these techniques used a scapula locator and
feedback from pressure sensors connected to locator probes to estimate the location of the scapula in space (Shaheen, Alexander, & Bull, 2011). This method was only reliable in slow to medium paced scapular movement and would be effective for tracking the scapula when rowing. Another technique used bone pins to determine the motion of the scapula in vivo (McClure, Michener, Sennett, & Karduna, 2001), but this technique is too invasive to have been used in the current study. Karduna et al. (2000) compared three methods of estimating scapular movement during dynamic movement. They compared the bone pin technique to the acromial method and a tracker method, where a tracker was developed involving a base, an adjustable arm, and a footpad. These three parts connect the mid-portion of the scapular spine to the acromion. It was found that the tracker method was more precise; however the acromial method was found to have an acceptable root mean square error making it a valid measure of scapular motion (Karduna, McClure, Michener, & Sennett, 2000). A study by Finley et al. (2003) used the Fastrak system (Colchester, VT) to measure scapular motion. They placed sensors on the sternum, the acromion process, and the humerus. In this experiment, they used the acromion process to describe the motion of the scapula during dynamic motion. They determined that the root mean square error due to skin artifact was between 2.0 – 9.4 degrees, which was established as acceptable to measure the dynamic scapular motion in their study (Finley & Lee, 2003). Based on the method used by Finley (2003), the movement of the acromion was used to measure the movement of the scapula. Therefore, the acromion was tracked in the current study. The less flexed the transverse shoulder angle was (closer to 180 degrees), the more the acromion was retracted. The more flexed the transverse shoulder angle was (closer to 100 degrees), the more the acromion was moved anterio-laterally.

Schmid et al. (2015) sought to validate two spinal angle measurement methods, radiography and skin marker-based motion capture. Reflecting skin markers were placed along the spinous processes of the thoracic spine and the thoracic curve was calculated using markers
T3-T12, which was the same method used in this study. In comparing these two methods, there was no substantial over estimation or underestimation of the thoracic spines in the sagittal plane and was deemed as a valid measurement of spinal movement (Schmid, et al., 2015).

There were some limitations to this study. Although the results of this study do show a change in shoulder angle with an increase in power, the number of participants could have been greater to strengthen the results of this study. With more participants, there may have been more athletes that did not exhibit the technique change and there may have been more that were able to maintain a less flexed shoulder angle until they reached a threshold. The difficulty of tracking the spinal processes was evident in this study, however, this potential problem was mitigated by finding the radius of curvature of the spine. Instead of assuming that the markers stay on each respective vertebra, it was assumed that the markers remained in line with the spine as the athlete performed the protocol, which poses its own limitations. As the ergometer was aligned in the lab’s coordinate system, it was assumed that the athlete maintained movement in the y-z plane with no rotation during the stroke. Since there is no rotation in the stroke on an ergometer, this seemed an acceptable assumption, although if the athlete did adopt a rotated position, this may have affected the thoracic spine angle. This was also exhibited in the tracking of the scapula. It was assumed that the athlete did not rotate during the stroke and that the majority of the movement occurred in the transverse plane. If the study was to be performed again, a scapula tracker could be used to have a better measure of scapular movement.

Other measures could also have been taken to attempt to explain more of the variance in the thoracic spine angle. A measure of trunk strength or lower leg strength would have beneficial to have been collected as well as a measure of trapezius strength. Some of the athletes were suffering from injuries at the time of testing. These injuries could have affected individual results, however, the athletes continued to train and compete at a high level with their respective club.
Therefore using injured athletes could lend insight into what movement patterns are potentially exacerbating their injuries.

5.2 Recommendations

The results of this study can be applied to real-world training situations. In terms of coaching, coaches should be watching for increased flexion of the shoulders as an athlete completes a workout. They should be aware of this collapse and potentially modify the workout to allow the athlete to recover. In addition to noting this shoulder collapse, the coach can recommend trapezius strengthening exercises. This would reduce the potential for the fatigue to the scapular retractors and reduce the risk of injury.

As an athlete training on an ergometer, it would be useful to understand at what power level their shoulders will enter increased flexion. For two athletes explored in these cases, the level at which one athlete saw increased shoulder flexion was 61% of their 2k power output while the other saw increased shoulder flexion at 80% of their 2k power output. It may be possible to use these thresholds in setting training goals that reduce the risk of injury for an athlete.

For future studies, it would be of interest to conduct a longitudinal study to determine if strengthening the scapular retractors would affect the rowers’ ability to maintain a supported posture during the drive phase. The athlete would perform a baseline scapular retractor strength test to establish a baseline. They would also perform a baseline ergometer test to observe scapular posture. Each athlete would then follow a strengthening program focused on the trapezius for a period of time, after which another test of scapular retractor strength would be performed. Then the ergometer test would be conducted and analyzed to determine a change in scapular position between the two tests.
Chapter 6

Conclusion

A fatiguing incremental ramp test elicited changes in rowing technique, specifically thoracic spine flexion and transverse shoulder flexion, in a group of 12 female rowers. Thoracic flexion was tracked using markers fixed to the spinous processes. Since tracking the scapula is difficult, tracking the acromion was used to indicate scapular motion, as was done by Finley et al. (2003). If the acromion changed position, it was likely that the scapula did as well. While the thoracic spine angle changed throughout the drive phase, it was not affected by increases in power output. However, there was an increase in transverse shoulder flexion as the rowers completed the test. Scapular movement suggests that as the transverse shoulder angle became more flexed with increasing power output, the mid-trapezius was not able to retract or hold the scapular position. Consequentially, the scapula moved anterio-laterally. The increased flexion of the transverse shoulder angle with increased power level indirectly supports the fatiguing of the retractors as a mechanism of injury. This mechanism of injury states that as the scapula move anterio-laterally, the vector that acts on the ribs has an increased posterior-anterior component applying an increased force to the ribs 4-9. If the scapula are retracted, the force acting on the ribs has a greater medio-lateral component, reducing the rib compression force.

Three different case studies suggest that to determine each athlete’s training level, they should be observed to examine at what power level their technique breaks down. From this information, a training zone can be prescribed to reduce the risk of a rib injury. For D01C and D25Y, those levels were 61% and 80% of their maximal efforts, respectively. In addition to this recommended training zone, coaches should be aware of shoulder collapse during a workout and allow the athlete either time to recover or modify the workout to reduce the risk of injury.
References


ROWONTARIO. (2014). *About Us*. Retrieved from ROWONTARIO:
http://www.rowontario.ca/about-us.html


Appendix A

Ethics Approval

QUEEN'S UNIVERSITY HEALTH SCIENCES & AFFILIATED TEACHING HOSPITALS RESEARCH ETHICS BOARD-DELEGATED REVIEW

July 11, 2014

Mr. Peter Sheahan
School of Kinesiology & Health Studies
Queen's University

Dear Mr. Sheahan

Study Title: PHE-146-14 Investigating the differences in spinal posture between dry-land (ergometer) and water-based training in elite level rowers.

File # 6013076

Co-Investigators: Ms. E. Price

I am writing to acknowledge receipt of your recent ethics submission. We have examined the revised protocol and revised information/consent form for your project (as stated above) and consider it to be ethically acceptable. This approval is valid for one year from the date of the Chair’s signature below. This approval will be reported to the Research Ethics Board. Please read carefully to the following listing of ethics requirements you must fulfill over the course of your study:

Reporting of Amendments: If there are any changes to your study (e.g. consent, protocol, study procedures, etc.), you must submit an amendment to the Research Ethics Board for approval. Please use our online Multi-Use Amendment Full Board Renewal Form associated with your post review file # 6013076 in your Researcher Portal (https://services.queen.ca/romeo_researcher).

Reporting of Serious Adverse Events: Any unexpected serious adverse event occurring locally must be reported within 2 working days or earlier if required by the study sponsor. All other serious adverse events must be reported within 15 days after becoming aware of the information. Serious Adverse Event forms are located with your post-review file # 6013076 in your Researcher Portal (https://services.queen.ca/romeo_researcher).

Reporting of Complaints: Any complaints made by participants or persons acting on behalf of participants must be reported to the Research Ethics Board within 7 days of becoming aware of the complaint. Note: All documents supplied to participants must have the contact information for the Research Ethics Board.

Annual Renewal: Prior to the expiration of your approval (which is one year from the date of the Chair’s signature below), you will be reminded to submit your renewal form along with any new changes or amendments you wish to make to your study. If there have been no major changes to your protocol, your approval may be renewed for another year.

Yours sincerely,

[Signature]

Chair, Health Sciences Research Ethics Board
July 11, 2014

Investigators please note that if your trial is registered by the sponsor, you must take responsibility to ensure that the registration information is accurate and complete.
Appendix B

Data sheet completed by participants

Rowing Questionnaire

Date: __________________

First letter of last name: __________________
Day of birth: __________________
Last letter of your street: __________________
Height: __________________
Weight: __________________
DOB: __________________
Gender: __________________

What is your most recent time on the following tests?

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<th>Split</th>
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Appendix C

Matlab code

Main script

clear all
close all

filename = dir('*.0*');
angleFoot = 45;
samplerate = 200;

for file=1:length(filename)
    loadF{file} = getQualisys(filename(file).name, 'analog', 1, [21]);
    handle{file} = getqualisys_N(filename(file).name, 'marker', 'handle');
    C7{file} = getqualisys_N(filename(file).name, 'marker', 'C7_');
    T12{file} = getqualisys_N(filename(file).name, 'marker', 'T12_');
    T10{file} = getqualisys_N(filename(file).name, 'marker', 'T10_');
    T7{file} = getqualisys_N(filename(file).name, 'marker', 'T7_');
    T4{file} = getqualisys_N(filename(file).name, 'marker', 'T4_');
    T1{file} = getqualisys_N(filename(file).name, 'marker', 'T1_');
    R_acrom{file} = getqualisys_N(filename(file).name, 'marker', 'R_acrom');
    L_acrom{file} = getqualisys_N(filename(file).name, 'marker', 'L_acrom');

    %    loadF{file} = naninterp(loadF{file});
    handle{file} = naninterp(handle{file});
    C7{file} = naninterp(C7{file});
    T12{file} = naninterp(T12{file});
    T10{file} = naninterp(T10{file});
    T7{file} = naninterp(T7{file});
    T4{file} = naninterp(T4{file});
    T1{file} = naninterp(T1{file});
    R_acrom{file} = naninterp(R_acrom{file});
    L_acrom{file} =naninterp(L_acrom{file});

    [b,a] = butter(4, 6/(200/2));

    handle{file} = filtfilt(b,a,handle{file});
    C7{file} = filtfilt(b,a,C7{file});
    T12{file} = filtfilt(b,a,T12{file});
    T10{file} = filtfilt(b,a,T10{file});
    T7{file} = filtfilt(b,a,T7{file});
    T4{file} = filtfilt(b,a,T4{file});
    T1{file} = filtfilt(b,a,T1{file});
    R_acrom{file} = filtfilt(b,a,R_acrom{file});
    L_acrom{file} = filtfilt(b,a,L_acrom{file});

    [Start, StartLoc] = findpeaks(-handle{file}(:,2), 'minpeakdistance', 100, 'minpeakheight',100);
[End, Endloc] = findpeaks(handle{file}(:,2), 'minpeakheight', 900, 'minpeakdistance', 100);

if (Endloc(1,:)<Startloc(1,:))
    for i = 1:length(Endloc)-1
        Endloc(i,:) = Endloc(i+1,:);
    end
    Endloc(end,:) = NaN;
    Startloc(end,:) =NaN;
end

for i = 1:length(Startloc)-1
    drive{file}.T12{i} = T12{file}(Startloc(i):Endloc(i),:);
    drive{file}.T10{i} = T10{file}(Startloc(i):Endloc(i),:);
    drive{file}.T7{i} = T7{file}(Startloc(i):Endloc(i),:);
    drive{file}.T4{i} = T4{file}(Startloc(i):Endloc(i),:);
    drive{file}.T1{i} = T1{file}(Startloc(i):Endloc(i),:);
    drive{file}.R_acrom{i} = R_acrom{file}(Startloc(i):Endloc(i),:);
    drive{file}.L_acrom{i} = L_acrom{file}(Startloc(i):Endloc(i),:);
    drive{file}.handle{i} = handle{file}(Startloc(i):Endloc(i),:);
end

%% Segment the force at the hands
for j = 1:length(Startloc)-1
    handDriveN{j} = loadF{file}(Startloc(j):Endloc(j),:);
    handRecoveryN{j} = loadF{file}(Endloc(j):Startloc(j),:);
end

for i = 1:length(handDriveN)
    drive{file}.handDrive{i} = 317.77*handDriveN{i}-450.04;
    drive{file}.handRecovery{i} = 317.77*handRecoveryN{i}-450.04;
end

for i = 1:length(Startloc)-1
    stroke{file}.time(i) = ((Startloc(i+1)-Startloc(i))/samplerate)/60;
    stroke{file}.rate(i) = 1/stroke{file}.time(i);
end

%% Radius of curvature
for strokeN = 1:length(drive{file}.T1)-1
    for pt = 1:length(drive{file}.T1{strokeN})
        % find radius of curvature
        ydrive = [drive{file}.T1{strokeN}(pt,2);
        drive{file}.T4{strokeN}(pt,2);
        drive{file}.T7{strokeN}(pt,2);
        drive{file}.T10{strokeN}(pt,2);
        drive{file}.T12{strokeN}(pt,2)];
        zdrive = [drive{file}.T1{strokeN}(pt,3);
        drive{file}.T4{strokeN}(pt,3);
        drive{file}.T7{strokeN}(pt,3);
        drive{file}.T10{strokeN}(pt,3);
        drive{file}.T12{strokeN}(pt,3)];
        [yfit, zfit, rad] = circfit(ydrive, zdrive);
mid = (drive{file}.T1{strokeN}(pt,3) + drive{file}.T12{strokeN}(pt,3))/2;

try
y1 = roots([1 -2*yfit yfit^2-rad^2+(drive{file}.T1{strokeN}(pt,3)-zfit)^2]);
catch
disp(file)
end

try
y12 = roots([1 -2*yfit yfit^2-rad^2+(drive{file}.T12{strokeN}(pt,3)-zfit)^2]);
catch
disp(file)
end

tyMid = roots([1 -2*yfit yfit^2-rad^2+(mid-zfit)^2]);
yMid=yMid(imag(yMid)==0);
catch
disp(file)
end

v1 = [y1(1), drive{file}.T1{strokeN}(pt,3)]-[yMid(1), mid];
v2 = [y12(1), drive{file}.T12{strokeN}(pt,3)]-[yMid(1), mid];

angle = dot(v2,v1)/(norm(v1)*norm(v2));
angleDegree = acosd(angle);

drive{file}.spineAngle{strokeN}.stroke(pt) = angleDegree;
drive{file}.spineRad{strokeN}.stroke(pt) = rad;
drive{file}.meanRdrive{strokeN}.stroke(pt) = radiusCurvature(ydrive, zdrive);
drive{file}.driveEnd{strokeN} = drive{file}.meanRdrive{strokeN}.stroke(end);
end

drive{file}.normSpineRad{strokeN} = timeNorm(drive{file}.spineRad{strokeN}.stroke,101);
drive{file}.normSpineAngle{strokeN} = timeNorm(drive{file}.spineAngle{strokeN}.stroke,101);
drive{file}.normSpineCurve{strokeN} = timeNorm(drive{file}.meanRdrive{strokeN}.stroke, 101);
drive{file}.normHandForce{strokeN} = timeNorm(drive{file}.handDrive{strokeN}, 101);
end

%% Find the max and average power during the drive
% power = force*distance/time
for i=1:length(drive{file}.T1)-1
    drive{file}.time(i) = length(drive{file}.handle{i})/samplerate;
end
%divided by frequency
distance = drive{file}.handle{i}(end,:) - drive{file}.handle{i}(1,:);
distance = sqrt(sum(distance.^2))/2000;
time = Startloc(i+1) - Startloc(i);
time = time/samplerate;
force = drive(file).handDrive{i};
power = force* (distance/time);
drive{file}.power{i} = power; %((drive{file}.handDrive{i}).*vNet');
% N*m/s
drive{file}.normPower{i} = timeNorm(drive{file}.power{i}, 101);
outcome{file}.POWER{i} = drive{file}.normPower{i};
clear power force vNet;
end

%% Angle of shoulders wrt eachother
for i = 1:length(drive{file}.R_acrom)
    for j = 1:length(drive{file}.R_acrom{i});
        upper(j,:) = drive{file}.T1{i}(j,2:3) -
        drive{file}.T4{i}(j,2:3);
        yaxis = [1 0];
        rotation =
        dot(upper(j,:),yaxis)/(norm(upper(j,:))*norm(yaxis));
        rotationDegree = (180 - acosd(rotation));
        R = rotx(rotationDegree);
        v1 = drive{file}.T1{i}(j,:);
        v2 = drive{file}.R_acrom{i}(j,:);
        v3 = drive{file}.L_acrom{i}(j,:);
        y1 = R*v1';
        y2 = R*v2';
        y3 = R*v3';
        b1 = y2(1:2) - y1(1:2);
        b2 = y3(1:2) - y1(1:2);
        drive{file}.theta{i}(j) =
        acosd(dot(b1,b2)/(norm(b1)*norm(b2)));
    drive{file}.normTheta{i} = timeNorm(drive{file}.theta{i}, 101);
end
clear magv1 magv2

%% averages for all the strokes at that effort level
for t = 1:length(drive{file}.T1)-1
    addP(:,t) = drive{file}.normPower{t};
    outcome{file}.meanPower = mean(addP')';
    outcome{file}.stdPower = std(addP')';
    addS(:,t) = drive{file}.normSpineAngle{t};
    outcome{file}.meanSpine = mean(addS')';
    outcome{file}.stdSpine = std(addS')';
    addSR(:,t) = drive{file}.normSpineCurve{t};
    outcome{file}.meanSpineRad = mean(addSR')';
    outcome{file}.stdSpineRad = std(addSR')';
    addT(:,t) = drive{file}.normTheta{t};
    outcome{file}.meanTheta = mean(addT')';
    outcome{file}.stdmeanTheta = std(addT')';
    addH(:,t) = drive{file}.normHandForce{t};
    outcome{file}.meanHandForce = mean(addH')';
    outcome{file}.stdHandForce = std(addH')';
    addThetaKnee(:,t) = drive{file}.normEulerKnee{t}(:,3);
    outcome{file}.meanThetaKnee = mean(addThetaKnee')';
    outcome{file}.stdThetaKnee = std(addThetaKnee')';
    addThetaHip(:,t) = drive{file}.normThetaHip{t};
outcome{file}.meanThetaHip = mean(addThetaHip')';
outcome{file}.stdThetaHip = std(addThetaHip')';
addStrokeRate(:,t) = stroke{file}.rate(t);
outcome{file}.meanStrokeRate = mean(addStrokeRate')';
outcome{file}.stdStrokeRate = std(addStrokeRate')';
end
end

%% Plot all the different outcomes ici
for file = 1:length(drive)
    [outcome{file}.maxHandForce,loc(file)] =
        max(outcome{file}.meanHandForce);
    outcome{file}.maxSpine = outcome{file}.meanSpine(loc(file));
    outcome{file}.maxPower = max(outcome{file}.meanPower);
    outcome{file}.maxShoulder = outcome{file}.meanTheta(loc(file));
end

load 'power.mat'
load 'powerSpine.mat'
load 'score.mat'
load 'scoreSpine.mat'

figure('Color',[1 1 1]);
for file = 1:length(drive)
    color = [01-1/file,1-1/file,1-1/file];
    subplot(3,3,1);
    plot(outcome{file}.meanHandForce,'color', color);
xlim([0 100])
xlabel('Percent drive phase (%)', 'FontSize', 12);
ylabel('Force (N)', 'FontSize', 12)
hold on
title('Hand Force', 'FontSize', 14)

subplot(3,3,2);
plot(outcome{file}.meanPower,'color', color);
xlim([0 100])
xlabel('Percent drive phase (%)', 'FontSize', 12);
ylabel('Power (watts)', 'FontSize', 12)
hold on
title('Power', 'FontSize', 14);

subplot(3,3,3)
plot(outcome{file}.meanTheta,'color', color);
xlim([0 100])
xlabel('Percent drive phase (%)', 'FontSize', 12);
ylabel('Angle (degrees)', 'FontSize', 12)
hold on
title('Shoulder Angle', 'FontSize', 14);

subplot(3,3,4);
plot(outcome{file}.meanSpine, 'color', color);
xlim([0 100])
xlabel('Percent drive phase (%)', 'FontSize', 12);
ylabel('Angle (degrees)', 'FontSize', 12)
hold on
%line([0 0],[0 drive{file}.percentMaxHF],'Color',color)
title(['Spine Angle', 'FontSize', 14]);

subplot(3,3,5);
plot(max(outcome{file}.meanPower), outcome{file}.meanStrokeRate, 'o', 'color', color);
xlabel('Power (watts)', 'FontSize', 12);
ylabel('Cadence (strokes/min)','FontSize', 12)
hold on
    title('Stroke Rate vs Power', 'FontSize', 14)

subplot(3,3,6);
plot(outcome{file}.maxPower, outcome{file}.maxShoulder, 'o', 'color', color);
xlabel('Power (watts)', 'FontSize', 12);
ylabel('Angle (degrees)','FontSize', 12)
hold on
    title('Max Shoulder Angle with Power level', 'FontSize', 14);

subplot(3,3,7)
    plot(outcome{file}.maxPower, outcome{file}.maxSpine, 'o', 'color', color);
xlabel('Power (watts)', 'FontSize', 12);
ylabel('Angle (degrees)', 'FontSize', 12)
hold on
    title('Max Spine Angle with Power level', 'FontSize', 14);

subplot(3,3,8)
plot(power, score, 'ko');
xlabel('Power (watts)', 'FontSize', 12);
ylabel('PCA score', 'FontSize', 12)
title('Shoulder 1st PCA score vs power level', 'FontSize', 14);

subplot(3,3,9)
    plot(powerSpine, scoreSpine, 'ko');
xlabel('Power (watts)', 'FontSize', 12);
ylabel('PCA score', 'FontSize', 12)
    title('Spine 1st PCA score vs power level', 'FontSize', 14);

end

PCA prep script

clear all
close all

filename = dir('**0**');
samplerate = 200;

for file=1:length(filename) 
    loadF{file} = getQualisys(filename(file).name, 'analog', 1, [21]);
R_acrom{file} = getqualisys_N(filename(file).name, 'marker', 'R_acrom');
L_acrom{file} = getqualisys_N(filename(file).name, 'marker', 'L_acrom');
T4{file} = getqualisys_N(filename(file).name, 'marker', 'T4_');
T1{file} = getqualisys_N(filename(file).name, 'marker', 'T1_');
handle{file} = getqualisys_N(filename(file).name, 'marker', 'handle');

R_acrom{file} = naninterp(R_acrom{file});
L_acrom{file} = naninterp(L_acrom{file});
T4{file} = naninterp(T4{file});
T1{file} = naninterp(T1{file});
handle{file} = naninterp(handle{file});

[Start, Startloc] = findpeaks(-handle{file}(:,2),
    'minpeakdistance', 100, 'minpeakheight', 100);
[End, Endloc] = findpeaks(handle{file}(:,2), 'minpeakheight', 900,
    'minpeakdistance', 100);

if (Endloc(1,:)<Startloc(1,:))
    for i = 1:length(Endloc)-1
        Endloc(i,:) = Endloc(i+1,:);
    end
    Endloc(end,:) = NaN;
    Startloc(end,:) = NaN;
end

for i = 1:length(Startloc)-1
    drive{file}.T4{i} = T4{file}(Startloc(i):Endloc(i),:);
    drive{file}.T1{i} = T1{file}(Startloc(i):Endloc(i),:);
    drive{file}.R_acrom{i} = R_acrom{file}(Startloc(i):Endloc(i),:);
    drive{file}.L_acrom{i} = L_acrom{file}(Startloc(i):Endloc(i),:);
    handDriveN{i} = loadF{file}(Startloc(i):Endloc(i),:);
    drive{file}.handle{i} = handle{file}(Startloc(i):Endloc(i),:);
end

for i = 1:length(handDriveN)
    drive{file}.handDrive{i} = 317.77*handDriveN{i} - 450.04;
end

for i = 1:length(drive{file}.R_acrom)
    for j = 1:length(drive{file}.R_acrom{i});
        upper(j,:) = drive{file}.T1{i}(j,2:3) -
    drive{file}.T4{i}(j,2:3);
        yaxis = [1 0];
        rotation =
            dot(upper(j,:),yaxis)/(norm(upper(j,:))*norm(yaxis));
        rotationDegree = (180 - acosd(rotation));
        R = rotx(rotationDegree);
        v1 = drive{file}.T1{i}(j,:);
        v2 = drive{file}.R_acrom{i}(j,:);
        v3 = drive{file}.L_acrom{i}(j,:);

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\begin{verbatim}
y1 = R*v1';
y2 = R*v2';
y3 = R*v3';
b1 = y2(1:2) - y1(1:2);
b2 = y3(1:2) - y1(1:2);
drive{file}.theta{i}(j) = acosd(dot(b1,b2)/(norm(b1)*norm(b2))); end

normTheta{file}(:,i) = timeNorm(drive{file}.theta{i}, 101); %drive{file}.end

for i=1:length(drive{file}.T1)-1
  drive{file}.time(i) = length(drive{file}.handle{i})/samplerate;
  %divided by frequency
  distance = drive{file}.handle{i}(end,:) - drive{file}.handle{i}(1,:);
  distance = sqrt(sum(distance.^2))/200;
  time = Startloc(i+1) - Startloc(i);
  time = time/samplerate;
  force = drive{file}.handDrive{i};
  power = force*(distance/time);
  drive{file}.power{i} = power; %((drive{file}.handDrive{i}).*vNet');
  % N*m/s
  Power{file}(:,i) = timeNorm(power, 101);
  clear power force vNet;
end

j=1;

for file = 1:length(normTheta)
strokes = size(normTheta{file});
  for i = 1:strokes(2)-1
    shoulderAngle(:,j) = normTheta{file}(:,i);
    shoulderAvgPower(:,j)= Power{file}(:,i);
    j = j+1;
  end
end

save('shoulderAngle.mat','shoulderAngle');
save('shoulderAvgPower.mat', 'shoulderAvgPower');

PCA script

clear all;
%close all;
clc;

load 'shoulderAngle.mat';
load 'shoulderAvgPower.mat';
Lift = shoulderAngle;
samplerate = 200;

fx = Lift;
\end{verbatim}
xtmean = mean(fx');

[xcoeff, xscore, xweighting, tsquarex] = princomp(fx');
[b,c,d,e,explainedx,mux] = pca(fx');

%

k =60 ;

figure(4);
subplot (1,3,1);
plot (fx);
title ('x');

xrecon = xscore(:, 1:k) * xcoeff(:, 1:k)';
subplot (1,3,2);
plot (xrecon');
title ('reconstructed');

xrecon = xrecon + repmat (xtmean, size(xrecon', 2), 1);
subplot (1,3,3);
plot (xrecon');
title ('reconstructed + mean');

score = xscore(:,1);
power = max(shoulderAvgPower);
save('score','score');
save('power','power');

Radius of curvature

function meanR = radiusCurvature(x, y)
%
% the function computes the mean radius of curvature for a given set of x-y coordinates
% credit for these algorithms should be given to Roger Stafford, who posted
% these algorithms on the MATLAB newsreader:
% http://www.mathworks.com/matlabcentral/newsreader/view_thread/152405
% http://www.mathworks.com/matlabcentral/newsreader/view_thread/294297#796465
%
% make sure that x and y are column vectors
x = x(:);
y = y(:);

if numel(x) < 3
    meanR = realmax('double');
elseif numel(x) == 3
    x21   = x(2) - x(1);
\begin{verbatim}
y21 = y(2) - y(1);
x31 = x(3) - x(1);
y31 = y(3) - y(1);
h21 = x21^2 + y21^2;
h31 = x31^2 + y31^2;
d = 2*(x21*y31 - x31*y21);
meanR = sqrt(h21*h31*((x(3) - x(2))^2 + (y(3) - y(2))^2)) / abs(d);

else
  \% take mean of coordinates
  mx = mean(x);
  my = mean(y);
  \% get differences from means
  X = x - mx;
  Y = y - my;
  \% get variances
  dx2 = mean(X.^2);
  dy2 = mean(Y.^2);
  \% solve a least mean squares problem
  t = [X, Y] \ ((X.^2-dx2 + Y.^2-dy2)/2);
  \% t is the 2 x 1 solution array [a0; b0]
  a0 = t(1);
  b0 = t(2);
  \% calculate the radius
  meanR = sqrt(dx2 + dy2 + a0^2 + b0^2);
end
end \% function radiusCurvature
\end{verbatim}
Appendix D

Individual summation of results

A01M