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To the Graduate Council:

I am submitting herewith a thesis written by McDaragh Rose Minnock entitled "Kinematic Analysis of Trunk Coordination Throughout the Rowing Stroke Sequence." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Kinesiology.

Joshua Weinhandl, Major Professor

We have read this thesis and recommend its acceptance:

Songning Zhang, David R. Bassett

Accepted for the Council:
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Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Kinematic Analysis of Trunk Coordination Throughout the Rowing Stroke Sequence

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

McDaragh Rose Minnock
May 2017

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Abstract

Rowing at the elite level requires proper sequencing of the rowing stroke so that the rower is able to produce an efficient stroke while protecting oneself from potential injuries. The cyclic motion of the rowing stroke sequence at low loads often results in overuse injuries, specifically in the lower back. Kinematic data of rower's pelvis-lumbar-thoracic spine were collected using inertial measurement sensors. An incremental step-test was conducted to observe the influence of increasing intensities on the lumbar-pelvis and lumbar-thoracic segments coordination and coordination variability. This study provides a new way of quantifying rowing kinematics using vector coding. The vector coding technique used in this study quantifies the relative motion and variability in lumbar-pelvis and thoracic-lumbar couplings during the rowing stroke. Rowers exhibited greater lumbar-pelvis coupling angle variability during the recovery-drive transition of the stroke sequence with increasing intensities, which may be necessary as the rower prepares for the added load applied when the oar is placed in the water. The findings from this study may also indicate that the low coupling angle variability during the drive and recovery phases of the rowing stroke could increase the demands placed on the lumbar and repeatedly stress the same surrounding tissues, potentially explaining the cause of overuse injuries seen in the sport.

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Chapter 1:

Development of the Problem

Background and Rationale

Rowing is a physically demanding sport that is unique from other sports in that the rower has to generate great amounts of power, coordination, and flexibility while performing the same exact rowing motion for thousands of meters. There are two seasons for rowing: head racing in the fall and sprint racing in the spring. Headraces are long distance races where teams compete on a 5000-meter racecourse, which test the athlete's high intensity endurance and power. Sprint racing season begins in the early spring and consists of a shorter distance of 2000-meters at all-out intensity to the finish line. Rowing is classified into two styles: sweeping and sculling. Sweep rowers use one oar, port or starboard, and have a pair partner who rows on the opposite side to keep the boat moving straight. Two oars are used per rower when sculling to propel the boat. Kleshnev et al. [1] estimated the force at the face of each blade to be 400 N for sculling and 800 N for sweep blades. Crew average nearly 230 strokes over the course of a 2000-meter race at the elite level. When teams are not racing on the water they either train in the weight room, cross train (running, biking, bleacher running, etc.), or most likely train on the rowing ergometer. Elite rowers are accustomed to long training sessions at varied intensities in order to increase power and aerobic fitness while also refining technique for improved form and efficiency.

Rowers at the elite level have perfected the simple rowing motion over countless training hours and stroke cycles, making it as efficient and powerful as possible. The rowing stroke sequence (Figure 1) is divided two phases and two positions: the catch position, drive phase, finish position, and recovery phase [1-3]. At the catch position, the oar blade enters the water at the start of the rowing stroke sequence. During the drive phase, the rower does the greatest

amount of work to propel the boat forward [1]. The rower is positioned towards the stern of the boat with their hips, knees, and ankles flexed and their upper extremities are extended out holding the oar handle. The drive phase is initiated by contraction of the quadriceps, which applies a force to the footplate, and extension of the legs downward. Next, the trunk and hips 'swing' open followed by bending of the arms. The arms and back act as a cantilever, which transfers the force applied to the footplate to the oar and face of the blade in the water [2]. The leg drive is responsible for generating most the force and power that get the boat moving in the first half of the drive phase [1]. The finish position concludes the drive phase, as the legs are extended and the blade is removed from the water. Boat velocity is greatest at this point in the rowing stroke sequence. The rowing stroke sequence is concluded by the recovery phase, where the athlete returns to the catch position and perform another stroke sequence. [2]. The drive time to recovery time ratio at low intensity/steady state rowing is recommended to be a 1:3 ratio, compared to high intensity rowing that is ideally a 1:2 ratio, but occasionally a 1:1 ratio [3]. The boat velocity builds throughout the drive phase as the rower applies large amounts of force to lift the boat out of the water. During the recovery phase, the boat "runs" or streams along the top of the water as the rower returns to the catch position to begin another stroke.

Alongside the rowers, coaches and coxswains provide feedback on technique for the rower to focus on each training session. Elite rowers are able to perform the same exact stroke over and over again, which puts great emphasis on the importance of rowing stroke efficiency. Rowers compete thousands of meters at low-moderate intensities each training session, and work to refine and improve this aspect of their stroke until it meets the coach's standards. Rowers are taught the proper stroke sequence in order to precisely apply power while reducing risk of injury [3].

The physically demanding nature of rowing and the repetitive loading and unloading of the athlete's body, along with long training sessions, increases their risk of developing an injury [4]. Considering that rowing is one cyclic motion and a non-contact sport, chronic and overuse injuries occur more frequently than acute injuries. Overuse injuries account for 72.1% and 69.5% of all rowing related injuries for females and males, respectively [5]. Lower back pain is the most prevalent, accounting for nearly 25% of all rowing related overuse injuries, followed by 22% of knee pain, upper extremity and ankle injuries 14%, and 9% of rib stress fractures [2, 6]. Incidence reports show that injury rates are highest during the fall and winter months when training is primarily performed on rowing ergometers [2, 7-9]. Elite level competition requires the athlete to be in peak physical condition; therefore, maintaining proper rowing form is paramount in injury prevention.

In previous research, researchers have suggested that the combination of repetitive loading and unloading of the lumbar spine at a low-moderate intensity plays a significant factor in lower back injuries [10, 11]. Other studies found the addition of fatigue with excessive lumbar flexion-extension can expose the rower to a higher risk of injury [11, 12]. The lumbar spine moves through a large ROM throughout the rowing stroke sequence, from 30° of flexion at the catch to 30-40° of extension at the finish. This large range of flexion and extension accounts for nearly 60% of the rowers available lumbar ROM. [11, 13, 14]. Adams and Dolan et al. [15] state that the vertebral structure and tissues undergo increased stress when lumbar flexion exceeds 50% of its available ROM. Considering the compressive forces the lumbar spine undergoes, proper form is important to reduce the forces placed on the rower's body [15, 16]. During mid-drive, the lumbar spine undergoes the greatest peak forces seen throughout the stroke sequence. As the rower nears the end of his or her leg drive and begins to extend the trunk with body

swing, shear and compressive forces at the lumbar spine are the greatest [14, 17]. Long training sessions exacerbate the risk of injury as fatigue can increase and the athlete's ability to control movements with precision diminishes [4, 11]. Hosea et al. [2] calculated the peak anterior shear forces of the lumbar spine during the rowing stroke to be 848 N and 717 N for males and females respectively. They also found the average compressive forces to be near 4000 N for males, and 3300 N for females, which were similar to measurements reported in several other studies [2, 11, 14, 18]. It is recommended that a single training session during practice should not exceed 30 minutes without a brief break to stop and stretch, however, this advice is seldom followed [19-21]. In a typical practice session, the athlete will often row between 20-25 kilometers with few rest breaks. During a standard training session the rower will have accumulated nearly 1800 flexion and extension cycles [10, 22]. This cyclic loading of the lumbar spine has damaging effects on the spinal structures and tissues. In a cadaveric study, Adams et al. [23] found the fluid in the intervertebral discs had reduced resistance to bending after repetitive loading. The addition of spinal rotation that is seen in sweep rowing adds the elements of torsional and lateral bending to the already heavily loaded lumbar spine. In scull rowing the body is loaded symmetrically, but in sweep rowing the athlete rotates out to one side and loads the body asymmetrically.

There is limited research available on the sport of rowing and trunk coordination throughout the rowing stroke sequence. However, there is research available related to trunk coordination during other movements, such as gait. The dynamical systems theory provides a viable technique for quantifying movement patterns [24, 25]. It provides a framework for modeling cyclic movements, which can be analyzed to interpret the coordination and variability between two adjacent segments. This technique provides information about the coordination and variability in the movement and the individual's response to the stimuli. Vector coding is a

common non-linear technique that falls under the dynamical systems theory. It analyzes data on an angle-angle diagram that is used to quantify movement coordination and variability between two adjacent segments throughout time [24, 25]. The vector orientation between the two consecutive points on the angle-angle diagram is referred to as the coupling angle and is represented by a value between 0-360° relative to the right horizontal. The coupling angle can then be used to describe the coordination of the adjacent segments as in-phase or anti-phase coordination patterns [24, 25]. Vector coding is beneficial when measuring the consistency or variability of the coupling angle over multiple cycles of a movement pattern, which is referred to as coordination angle variability. Variability in movement tasks has often been viewed as a negative influence on the body or system. It raises awareness to researchers or clinicians about possible underlying dysfunctional or clinical issues. However, conflicting arguments state that variability in movement is necessary to adjust to sudden stimuli. The complex relationship between coordination and variability may explain why elite athletes are able to repeatedly perform swift changes in dynamic movements [25-27].

Statement of the Problem

Lower back injuries are the most prevalent type in the sport of rowing. The long training sessions in combination with the repetitive loading and unloading of the lumbar spine at low-moderate intensities increase the risk of the rower of developing an injury. However, it is still not known at what rowing stroke intensity a rower begins to deviate from proper rowing form, or how rowing stroke intensity influences pelvis-lumbar-thoracic spine coordination.

Statement of Purpose

The purpose of this study is to observe the influence of rowing stroke intensity on thoracic-lumbar and lumbar-pelvis coordination. Kinematics of the rowing stroke sequence from

elite rowers competing on the University of Tennessee Varsity Rowing Team will be collected and analyzed to describe the changes in motion as rowing intensity increases. An incremental step-test will be implemented to facilitate changes in kinematics from moderate rowing intensity to vigorous rowing intensity. The individual rower's average 2000-meter ergometer test split will be used to determine their specific split-time rowing intensity.

Research Hypotheses

Question 1: At what rowing intensity does the rower start to deviate from proper rowing form?

Hypothesis 1: The rower will begin to deviate from proper rowing form at 90% split intensity.

Question 2: How does rowing stroke intensity influence thoracic-lumbar and lumbar-pelvis spine coordination variability?

Hypothesis 2: Variability in thoracic-lumbar and lumbar-pelvis spine coordination will increase as the rowing stroke intensity increases.

Limitations of the Study

1. Rowing split intensity is calculated from the previous season's 2000-meter ergometer test. Fitness on the day of the test may differ from previous season's split.
2. Split-time varies with each individual stroke. Participant will have to stay within ±1 seconds of their goal intensity (i.e. split-time).

Delimitations of the Study

1. Participants will be between the ages of 18-25 years old.
2. Participants must be current members of the University of Tennessee Varsity Women's Rowing Team.

3. The participant must answer the self-scored lower back pain scale less than or equal to 3/10 on the day of the data collection.
4. Participants will be excluded from the study if they have received back surgery, or any injury within the past 6 months.
5. Data will be collected on the same model rowing ergometer used by the University of Tennessee Rowing Team so that participants will be familiar with the equipment.

Assumptions of the Study

It is assumed that all rowers are proficient in rowing and use proper form and loading of the body throughout the rowing stroke sequence. Since there is no rotation of the trunk as seen in sweep rowing, it was assumed that there would be no spinal rotation on the ergometer. All movement in the rowing motion was assumed to occur in the sagittal plane.

Significance of the Study

This study seeks to identify the point at which the rower deviates from proper rowing form, which may provide an explanation for the high prevalence of lower back injuries in collegiate rowing. It will provide information about the mechanical demands placed on the trunk segment during strenuous activity. It will also provide a more accurate representation of the trunk kinematics via a multi-segmented trunk rather than a rigid segment, which has been seen in other literature.

Operational Definition of Terms

Bow – The front and forward direction of the boat; the first part of the boat to cross the finish line.

Cantilever – A rigid structural element anchored at only one end.

Catch – When the oar blade enters the water.

Coxswain – The person who steers the boat and gives commands to coach the rowers.

Double – A sculling boat with two rowers; (2x).

Drive– The portion of the stroke sequence that propels the boat through the water. The legs extend, hips swing open, and arms draw in. Is initiated by the catch and is completed by the finish position.

Eight – An eight-person sweep boat steered by a coxswain.

Ergometer – "Erg" indoor rowing equipment.

Feather – The oar blade positioning parallel to the surface of the water

Finish position – The third phase in the rowing stroke sequence. The legs are extended.

Footplate – The part of the boat/erg where the feet are fastened.

Four – A sweep boat with 4 rowers.

Headrace – 5000-meter race.

Ideal form – Average coupling angle of 225° during the drive phase and 45° during the recovery phase.

IMU – Inertial measurement unit (sensors).

Pair – Two-person sweep boat.

Port – The left side of the boat when facing in the direction of the bow.

Quadruple – A four-person sculling boat, typically does not include a coxswain.

Recovery – The final phase of the rowing stroke sequence when the rower returns to the catch position to begin another stroke sequence. Arms extend out, trunk pivots forward at the hips, legs flex and the rower is in the correct positioning to take the next stroke.

ROM – Range of motion.

Rower – The athlete who participates in the sport of rowing.

Segmental dominancy – Refers to the proximal or distal segment that has more motion relative to the adjacent segment.

Sprint race – 2000-meter race

Split – Refers to the amount of time it takes to complete 500 meters of rowing.

e.g., 2:00 min/500 meter

Starboard – The right side of the boat when facing in the direction of the bow.

Stern – The rear/back of the boat. Rowers face this direction.

Stroke rate – The frequency of strokes taken in one minute (e.g., 18 strokes per minute).

Sweep – Refers to the style of rowing where each rower has one oar, and is matched up with a pair-partner who rows on the opposite side of the boat.

Chapter 2:

Review of the Literature

Introduction

The purpose of this study is to observe the influence of rowing stroke intensity on thoracic-lumbar and lumbar-pelvis spine coordination; therefore, this chapter will present a review of existing literature describing the rower's training volume and equipment used in relation to injury reports. Rowing is a highly competitive and well-known international sport that is credited by the athlete's training regimen and physical requirements. Athletes at an elite level of competition train at a frequency and intensity where their bodies are more susceptible to injury. Previous studies have shown a strong correlation between the amounts of training, level of experience, and the type of equipment used with reported injuries. This review of literature will provide an overview of possible mechanisms of injury and common injuries rowers of all competition levels might experience. This study may identify the point at which the rower deviates from proper rowing form, which may provide an explanation for the increased prevalence of lower back injuries in collegiate rowing.

Background of Rowing

Rowing is a leverage sport, where the athlete's height and strength are critical factors in producing maximal stroke power. Although there are different thoughts on which technical aspects of the rowing stroke are most important, the overall sequence is the same. The rowing stroke can be broken down into four parts: the catch position, drive phase, finish position, and recovery phases [2, 28]. The stroke sequence begins with the catch position where the blade enters the water. The body is fully compressed towards the stern of the boat, the arms are extended holding the oar handle, neutral alignment of the spine, anterior tilt of the pelvis, and the

hips and knees are flexed. The drive phase is initiated by the contraction of the quadriceps and the force is applied to the foot stretchers [2]. Once the knees approach full extension, the hips and back begin to extend, and is referred to as “body swing”. During the drive phase, the back muscles are engaged, holding the spine in neutral alignment, while the arms are fully extended gripping the oar handle. The arms and back act as a cantilever to connect forces placed on the foot stretchers to the oar blade in the water in order to generate propulsion of the boat [2, 28]. The drive phase is completed as the arms draw the oar handle into the body to finish the stroke. The finish position concludes the drive phase. At the finish position, the body is fully extended with the oar handle at the bottom of the rib cage, so the blade can be removed from the water and feathered parallel to the water surface. This is the point in the stroke where the boat is moving at maximum speed.

The recovery phase concludes one full stroke sequence. The recovery phase is the reverse body sequencing of the drive phase: first the arms extend out away from the body, then the rower pivots forward at their hips with a neutral spine, lastly the legs flex with control so the body is once again compressed towards the stern. As the rower recovers and approaches the catch position, they square their blade up and are ready to begin another stroke sequence.

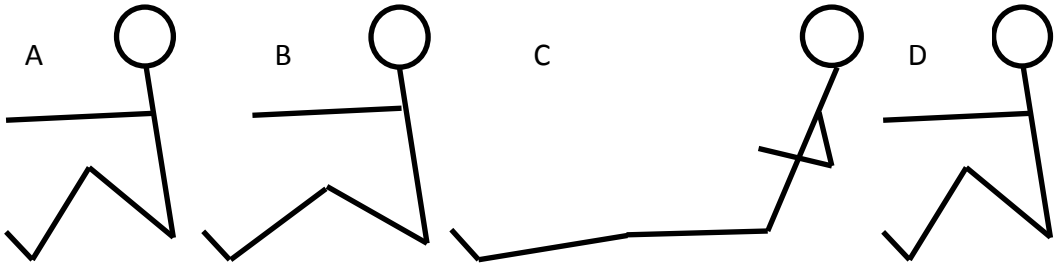

Figure 1. The rowing stroke sequence starting with the catch (A), followed by the finish (C) and subsequent catch (D). The drive phase is initiated at the catch and is concluded at the finish (A-C). The recovery phase is initiated at the finish position and concludes at the catch position of the next stroke (C-D).

Styles of rowing

The sport of rowing is classified into two styles: sweeping and sculling. The scull style of rowing is when the athlete has two oars, one for each hand. The rower is able to manipulate the speed and direction of the sculling boat by adjusting the pressure applied to each oar. Sculling events include the single (1x), double (2x), and the quadruple (4x). The rowing motion in a sculling boat is very similar to that of the rowing ergometer. When sculling, the spine is in neutral alignment; the arms are extended out to their respective side. Once the blades are placed in the water, the stroke sequence begins by pressing on the foot stretchers to evenly distribute pressure on the oars so the boat goes straight. In sweep rowing, the athlete only has one oar that is manipulated with both hands; therefore, they rely on a pair-partner who rows on the opposite side to keep the boat moving straight. The rowing sequence is similar to that of a sweep boat, although an element of spinal rotation and asymmetrical loading of the body is added at the catch and throughout the drive phase [20, 29]. Sweep rowing events include pairs (2-), fours (4 +/- with or without coxswain), and eights (8+).

Coaching

Athletes are coached extensively in proper technique and practice at varying intensities in order to increase fitness and protect from developing an injury. Training occurs on land and water, which includes a combination of weight lifting, running, rowing on the ergometer, and rowing on the water with the purpose of improving the athlete's physical and technical abilities [30]. Training regimens are designed at varying intensities to build the athletes aerobic capacity and power output [14]. Ergometer and rowing specific training regimens determine rowing intensity by the amount of time it takes to complete 500-meters; this time is referred to as a split-time. The coach's objective when addressing the athlete's execution of the rowing stroke

sequence is two-fold: 1) performance and 2) injury prevention. From a performance standpoint, a coach attempts to improve the rower's technique, in order to allow the athlete the capacity to replicate proper stroke mechanics over a long duration training session, which ultimately leads to faster race times. Due to the repetitive nature of rowing, proper technique is important in reducing the risk of injury.

The athlete is expected to hold proper technique throughout training sessions in order to produce the best times and minimize risk for potential injury. This remains true whether the athlete is training for endurance races or sprint races. The stroke sequence is performed cyclically over thousands of meters while exerting maximal power to propel the boat forward repeatedly throughout training sessions and competitions. The physically demanding nature of rowing at a vigorous intensity level is likely to result in injury that can impact ones rowing career [2]. Buckeridge et al. [14] Fohanno et al. [20], and Hosea et al. [2] found in each of their respective studies that the repetitiveness, and asymmetrical motion in sweep rowing, put abnormal stressors on the rowers body, which could potentially be a pathological mechanism for injury development. Injuries sustained due to overuse of particular muscle groups and/or repetitive compressive forces on the lumbar spine are largely left untreated. This is because athletes prioritize their ranking on the team and largely choose to endure the pain and discomfort rather than miss practice. Lower back pain is accompanied by a range of issues varying in severity, for example: muscle soreness, neurological impingement, spondylosis, herniated disc, and disc degenerative, and bone spurs [2, 10, 31]. Thus my thesis proposal is centered on the unique aspect of rowing injuries. I am interested in how the rowing stroke intensity influences thoracic-lumbar and lumbar-pelvis coordination at increasing stroke intensities.

Prevalence of Injury

Chronic overuse injuries are the most predominant type of injuries among rowers due to the repetitive movement of the sport. Low back pain has been the most prevalent injury among rowers, accounting for about 25% of all injuries in the sport [32]. Teitz et al. [21] surveyed 4,680 former intercollegiate rowing athletes, who graduated between the years 1978 and 1988, about their rowing experience. A total of 2,165 former rowers returned completed surveys assessing their back pain and practice time lost due to injury while competing, of which only 1,632 (935 men, 693 women) met the inclusion criteria for analysis. Of the 1,632 total respondents, 32% had experienced back pain (297 men, 228 women) at some point throughout their rowing career [21]. There were 508 respondents able to identify when the low back pain began. Teitz et al. also reported 72% lost a month of practice or less due to their injury.

Newlands et al. [32] conducted a prospective cohort study investigating low back pain among representatives of the 2011 New Zealand national rowing team. Rowers completed an online questionnaire once a month over a 12-month period, which evaluated non-modifiable risk factors, level of competition, rowing discipline, and history of low back pain. A follow-up survey evaluated the severity of low back pain they were experiencing in addition to the training volume and intensity from the previous 4-weeks. To differentiate between pre-existing and new low back pain, a physical examination and a series of mobility tests were performed prior to the start of the study [32]. Newlands et al. found the prevalence of low back pain throughout the year ranged from 6% to 25% of the New Zealand national team representatives. Of the 76-rowers, 817 questionnaires were returned and 40 rowers (52.6%) had experienced at least one episode of low back pain over the 12-months. Of the 40 rowers, 75% reported low back pain for two or more consecutive months. A high, positive correlation was seen between the total number of training

hours per month and low back pain reported [32]. This relationship was true for the number of ergometer training hours, on the water training hours, and the average distance rowed per participant per month.

In a similar retrospective cohort study conducted by Smoljanovic et al. [7] surveyed several hundred senior rowers at the Senior World Rowing Championships. The aim of their study was to identify types of musculoskeletal injuries present in senior international rowers [7]. A total of 634 senior rowers completed a four-page, 12-month retrospective survey about personal and general rowing information, specific rowing information from the previous year, and any injuries within that year. Upon completion of the survey, the rowers were interviewed about specific details of their injuries, which were most commonly located at the L4/L5 and sacrum [7]. The aforementioned studies investigated the prevalence of injuries among rowers and the etiology behind them such as overuse, training equipment, and forces placed on the body [2, 7, 29]. In a previous study observing elite junior rowers, 78.3% of the respondents reported having an overuse injury at some point throughout their rowing career [8]. The severity and location of the injury can hinder an athlete's participation in training, or cause absence from training all together [7, 8, 29]. Identifying potential causes and risk factors of injuries is critical so athletes can continue training without further injury or absence from training.

Injury reports have been used to classify the rower's level of competition to the type of injury developed. Verrall et al. [28] examined the prevalence of injuries among national and international rowers that resulted in a loss of training time. They found that international team members, with higher volumes of training, were more likely have a rib stress fracture while national team members were more likely to sustain injuries to their lower backs; hence suggesting they had less experience [28]. Common findings throughout these studies indicate

that the amount of time a team member spends rowing (volume) at competitive levels of training (intensity/experience) are related to the type of injury they incur. They found that most of the respondents had suffered from a rowing-related injury that prevented them from participating in practice for some portion of time.

Training Volume

There are two seasons for rowing: head racing, which occur in the fall, and sprint racing, which occurs in the spring. Headraces are long distance races, which take place over a 5000-meter course and typically function as high intensity endurance training to build the athletes stamina in preparation for sprinting. Sprint races occur along a 2000-meter straight course where the boats line up and race in a maximum effort sprint to the finish line. Since collegiate rowing takes place in the fall and the spring seasons, the majority of the training done during the winter months is performed on the rowing ergometer. The rowing ergometer is a great instrument to help athletes stay in top physical condition and train in the same manner as though they were on the water. However, higher rates of injuries have been reported during the winter months during the peak usage of ergometers [29]. Wilson et al. [33] and Hosea et al. [2] proposed that training volume is one of the leading causes of chronic overuse injuries among rowers. In several studies, it was recommended that continuous training should not exceed 30 minutes without a break period [2, 20, 21]. This is to allow a rower to stretch their bodies before beginning another segment of training and reducing the risk of developing a lumbar spine injury.

Wilson et al. [34] compared lumbar spine motion in the sagittal plane during ergometer rowing and rowing in a single scull boat over the course of a maximal effort test. They found that the amount of lumbar flexion increased significantly on the ergometer compared to in the boat, 4.4° ± 0.9° and 1.1° ± 1.1° respectively [34]. Wilson et al. [34] reported an increase in the

lumbar sagittal flexion as the duration of the training session increased; especially during ergometer training. This study was able to compare the lumbar kinematics between ergometer rowing and sculling to see how fatigue affects kinematics. An electrogoniometer was used during a step-test for both the rowing ergometer and on the water in the sculling boat to measure the sagittal lumbar kinematics. This study was very informative by comparing the training tool with the actual equipment rower's use. They found that as the step-test progressed, there was an increase in sagittal lumbar movement by 11.3% on the rowing ergometer, whereas minimal changes were observed on the water rowing [34].

As the training session progresses, rowers begin to feel the effects of fatigue and have decreased precision of controlled movements, putting them at risk of injury [4]. Caldwell et al. [11] suggested that the fatigue prevents the rower from having an accurate sense of lumbar positioning and body control towards the end of training sessions.

Kinematics and Kinetics of Rowing

Rowing has evolved from the simple boat and oar to a very sleek and methodical sequence of the whole body to generate the most powerful and efficient stroke. Rowing is unique from other sports because the athlete is facing backwards, moving their boat in the forward direction. The back acts as a braced cantilever to connect the force applied on the face of the blade to the force applied on the foot stretchers [2]. The forces placed on the rower's body over time, in conjunction with the cyclic rowing sequence, can lead to potential injuries on the rowers' body [2, 11]. A thorough understanding of the kinematics of the rowing stroke will give better insight to the causes of injuries among rowers and could reveal potential modifications to the rowing technique to reduce injury risk.

d'Ailly et al. [29] measured the acceleration of the seat in the first quarter of the drive phase of rowers experiencing pain in their ribs and compared the findings to the control group of rowers not suffering from rib pain. Reflective markers were placed on the handle, the seat, and anatomical landmarks of the rower's body. Those who suffered from rib stress fractures appeared to have a higher initial seat velocity than those who did not suffer from an injury [29]. The higher initial seat velocity could be associated with the development of rib stress fractures and low back injuries because the load is being shifted onto the rower's back faster than in the control group.

Although strength and endurance improves with training, the athlete is likely to over-compensate for fatigue through the modification of their stroke sequence towards the end of each training session in order to meet the performance standards. Caldwell et al. [11] examined the effects of the cyclic rowing motion on lumbar flexion. The largest amount of forward flexion of the lumbar spine at the catch phase and extension occurs at the finish [17]. Previous research shows that the range of motion at the trunk to be positioned at 30° flexion at the catch position, and between 20-30° extension at the finish [11, 13]. This exposure to large range of motion along with repetitive loading and unloading of the spine is likely to alter joint mechanics and loading pattern of the lumbar spine, especially when combined with fatigue.

Caldwell et al. [11] studied how lumbar flexion angles change when the rowers are experiencing fatigue. Kinematic motion data and electromyography data were collected at three points (20, 60, and 95%) over a 2000-meter maximal effort ergometer test. It was designed to push the participants to exhaustion to then examine how fatigue influenced performance and technique. Flexion was measured as a percentage of the difference between standing position and a sit and reach test, except hands were placed behind their head [11]. The rowers were at their

most flexed position during 50-60% of the drive phase, with the spine between 74-89% of total flexion. Results indicated that flexion increased from 75 to 90% of max range of motion as the rowing trial progressed [17].

The final quarter compared to the initial quarter of the drive phase showed more lumbar flexion and high compressive forces on the lumbar spine [11, 13]. This increased flexion over long training periods potentially exposes the rower to an increased risk of injury because of the forces being applied to the lumbar spine and soft tissues in a state of vulnerability. Muscle activity reached maximum values during the middle of the drive phase. Muscle activity also increased over the three stages of the test trial.

The lower back provides an additional source of power throughout the full range of motion of the rowing stroke sequence [2]. Over the course of a high-intensity or long duration training session, the range of motion experienced at the lower back can vary as a result of fatigue. Buckeridge et al. reported the repetitive flexion and extension loading on the lumbar spine, in combination with exhaustion increases the risk of tissue failure and low back injury [11, 16, 18, 35]. Buckeridge, Bull, and McGregor conducted a step-test where they manipulated the stroke rate, to mimic intensity, and collected kinetic and kinematic data using a 3D camera system [14]. As the stroke rate increased, a corresponding increase in peak L5/S1 extensor muscle moments was observed, increasing lower back stress. The increased stress, in addition to the repetitive flexion and extension of the back, places large amounts of force on the vertebral structures. Deviation from the proper form increases the loads placed on the back throughout the stroke sequence rather than being transferred to the oar.

The shear and compressive forces experienced on the lower back are similar in both ergometer rowing as well as sculling; however, the additional component of spinal rotation seen

in sweep rowing adds torsional and lateral bending stress to the low back [2]. The peak compressive force is greatest during the mid-drive phase as the rower begins to extend the spine and the upper body passes over the pelvis. Hosea et al. calculated compressive forces to be 6.8 times (in females) and 7 times (in males) body weight during this part of the drive phase [2]. Morris et al. [35] noted that the peak anterior shear loads on the lumbar spine during a simulated race piece averaged 4.6 times the participant's bodyweight. The peak compressive and shear loads shown on the ergometer mirror the force at the oar handle when taking the catch.

A similar study of lumbar motion, by Wilson et al. [30] investigated the relationship of fatigue and changes in kinematic of the lumbar spine in the frontal plane [34, 36]. An incremental step-test with increase in stroke rate and split intensity was conducted to observe angular displacement of the lumbar spine in the frontal plane. Upon finishing each level of the step-test, a blood sample was drawn to measure lactate levels to indicate fatigue over the trial. The step-test was performed on a Concept II model D rowing ergometer, and a Spectrotilt RS232 Electronic Inclinometer measured angular displacement of the rower's trunk at L3 [34]. This study was the first to measure frontal plane angular displacement during ergometer rowing because previous researchers made the assumption that no motion occurs since there is no spinal rotation [34]. However, Wilson et al. found lumbar displacement to be higher as the timed test progressed, and attributed it to fatigue. They reported a 4.1°±1.94 increase in frontal plane angular displacement from the first to last phase [33, 34]. This study and the one conducted by Caldwell et al. examined fatigue and lumbar flexion; however, they used different variables to measure fatigue [11, 33, 34]. Wilson et al. found that measuring blood lactate was not a good indicator of fatigue because it was not related to the performance decrement. Rather, the increase in stroke rate as the step-test progressed was a better indicator of fatigue [34]. At increased

stroke rates there was more angular displacement in the frontal plane when compared to the lumbar flexion from the end of the step-test to the beginning [34]. For the purpose of this thesis, a similar methodology to Caldwell and Wilson's was used to analyze the increase in rowing stroke intensity and its influence on pelvis-lumbar-thoracic coordination.

Equipment

For training purposes, it is imperative to have a piece of equipment that accurately measures the work being exerted by the athlete because it is helpful to coaches and athletes to monitor the power produced and progress. This is especially important for a team sport like rowing where one person's work on the water cannot quantitatively be differentiated from the other rowers in the boat.

Ergometer

The Concept II rowing ergometer is a popular piece of equipment that has undergone many modifications in order to be the most appropriate training tool for rowers. The Concept II ergometer is equipped with software that measures the stroke-by-stroke power output, the rate of each stroke, and has been validated by Macfarlane, Edmond, and Walmsley [37]. The variables of interest in this validation study were: force at the handle, velocity at the handle, force at the feet, heart rate monitoring and conditioning. They were also interested in ensuring the calibration was accurate for the following: calibration of the force transducer, calibration of the velocity of the handle, calibration of the force at the feet, heart rate transducer calibration, electronic calibration of the data-acquisition system, and software data processing. Seven experienced male rowers participated in a maximal effort 90-second ergometer test. A second 90-second maximal effort was conducted no more than 2 days following to ensure test-retest reliability [37]. Results from the first testing session were compared to the retest scores using a 2-way ANOVA, which

confirmed reliability for all variables (*p=0.05*) except for power maintenance and the percentage of work done in the last quintile of the stroke sequence [37].

Schabort et al. [38] investigated the reliability of performance over a 2000-meter timed-trial on the Concept II rowing ergometer. Preliminary testing involved a progressive incremental power test to exhaustion to measure max oxygen uptake and power output of eight trained high school varsity rowers. Three days following the preliminary assessment, rowers performed the first of three 2000-meter maximal effort timed-trials. All testing trials were performed on a Concept II ergometer with the damper vents set on 4 [38]. Heart rate, average power output per 500 meters, and total time were the variables of interest in this study. Results showed an improvement of 2% between timed-trial 1 and time-trial 2; a 0.9% improvement was found between time-trial 2 and time-trial 3. Schabort et al. [38] attributed this slight between test improvement to test familiarization and increase in fitness since the participants were of high school age. The study found that the coefficient of variation for power was the most appropriate assessment of reliability. Athletic performance tests are useful for gauging individual improvements from training and allow for unbiased comparisons between athletes. The Concept II rowing ergometer is a reliable instrument to measure power output and a practical tool to analyze the rowing stroke sequence.

There are two types of Concept II ergometers: slide-based ergometer and stationary ergometer. Slide-based ergometers are designed to simulate what it is like to row on the water, so the feet and seat move throughout the rowing sequence. Training on the slide-based ergometer has been observed to lower the forces placed on the rowers' body when compared to rowers using a stationary ergometer [33, 36, 39].

The propulsive forces at the handle of a stationary ergometer are a direct result of accelerating the rower's body mass against the ergometer to generate force at the handle. This force is positively related to the magnitudes of compressive forces in the lumbar spine and bending of the vertebral structure [36]. The slide-based ergometer is suspended on slides so it moves in a more authentic motion like a boat through the water. Although the power output is similar between the slide-based and stationary rowing ergometers, the study of Vinther et al. found a decrease in initial handle force on the slide-based ergometer compared to the stationary ergometer which decreases the load produced on the body [36]. These "decreases" in force production of slide-based versus stationary rowing do not decrease the speed of the boat, rather it changes how the forces produced are dispersed throughout the body. Holsgaard-Larsen et al. [39] observed 3.7-9% lower mean force and 3.2-10.6% lower peak force on the slide-based ergometer compared to the stationary ergometer when exerting maximal effort. In the book *Rowing Faster* written by Nolte et al. [3], they describe how the forces experienced by the lower back that are produced at the erg/oar handle and the foot stretchers. The lower back is described as a dynamic junction where the descending loads from the handle meet the ascending loads from the foot stretchers [1, 3].

Vinther et al. [36] conducted a study where they investigated the neuromuscular activity and force loads produced on the body on stationary versus slide-based ergometers by utilizing electromyography (EMG) to look at the neuromuscular activity in the thoracic muscles and leg muscles. A 6-minute sub-max test at self-selected stroke rate was performed on stationary and slide-based rowing ergometers on two separate occasions. Data were collected for handle force and rate of force development, and EMG data of selected leg and thoracic muscles [36]. Peak force decreased by 76 N in males and 20 N in females on the slide-based rowing ergometer

compared to the stationary rowing ergometer. The neuromuscular activity differed more in the leg muscles than the thoracic muscles when comparing the slide-based to the stationary rowing ergometer. The rate of force development also decreased by 20.7% in the slide-based ergometer compared to the stationary ergometer [36]. The reason for these differences between rowing ergometers results is their position relative to the ground. The athlete has to accelerate their body mass to generate force at the handle when rowing a stationary ergometer. A slide-based rowing ergometer requires the athlete to only move the mass of the ergometer [36, 40], thus decreasing the demands placed on the athlete and neuromuscular activity.

The study of Caldwell et al. [11] examined lumbar flexion and also used EMG to monitor the major thoracic muscles involved in the rowing stroke to observe their activity over the 2000-meter maximal effort ergometer test. Maximum voluntary isometric contractions (MVC) for muscles of interest was measured to compare muscle activity throughout ergometer test [11]. The drive phase was divided into 10% increments and examined lumbar flexion at 20%, 60% and 90% of the drive phase [11]. The researchers mention that these specific points in the drive phase are related to the maximal lumbar flexion and compressive forces on the lumbar spine. They found peak muscle activation in the middle of the drive phase as the legs reached full extension and the “body swing” extends the trunk over the hips. Muscle activity also increased across the three stages of the ergometer test from nearly 50% of MVC to almost 80% of MVC at the end of the trial [11].

IMU Sensors

Sport-related research struggles to bridge the gap between real-life competition and laboratory studies. One way to obtain information from the rowing motion and key variables of interest is to utilize inertial measurement unit (IMUs) system. Tessendorf et al. [41] utilized the

IMU-based sensor network to monitor the rowing stroke technique on the water in an attempt to bridge this gap. Inertial measurement unit sensors were attached to the boat and the oar and calculated the orientation angle between them. From the placement of the IMUs on the boat and oars, the researchers were able to collect data concerning stroke length, stroke rate, and ratio of the recovery/drive. Ambitious amateurs as well as national rowing team members participated in the study to quantify proficiency in rowing technique. The IMU sensors placed on the oars provided information on the oars rotation angle at each time point throughout the stroke, and were independent of the absolute boat movement [41]. The IMU sensors on the boat provided information on the boats acceleration. The information collected from the trial provides the coach with a more comprehensive understanding of the rower's technique and how it influences boat speed. Although their visual assessment of the rowers form offers tremendous and meticulous feedback about the athlete's form, several aspects about rowing form are difficult to analyze without additional equipment. The study found that evident differences in efficiency of technique exist between the ambitious amateur rowers and the national team members by using the IMUs [41]. This is known information that a world-class rower is faster than an amateur; however, the utilization of the IMU sensor system was able to measure and generate data about the specific instances throughout the rowing stroke. Although this study investigated rowing technique with IMU placement on the rowing equipment rather than the athletes, it quantified variation in technical proficiency with skill level. Research is no longer restricted to the laboratory; IMU-sensors make data collection feasible in competition settings.

Bosch et al. [42] utilized IMU sensors to compare technical proficiency between novice and experienced rowers. Sensors were placed on the leg, lower back and upper back to track postural changes in experienced rowers and compared them to novice rowers. Data were

collected from an incremental step-test at increasing stroke rates and split-intensity to identify measurable postural differences that are indicative of experience level and technical proficiency. They found that that absolute postural angle of the segments was not a good indicator of experience level, however, standard deviation was more indicative of experience level and technical consistency [42].

Quantifying Coordination Variability

The dynamical systems theory provides a viable framework for modeling athletic performances. It allows the researcher to interpret coordination and coordination variability between two segment angles. The ability to quantify variability between the segments provides information about the participants coordination and response to stimuli [24, 26, 27, 43]

Variability in movement patterns is typically viewed as a negative influence on the system [41]. However, variability in a movement tasks raises awareness for researchers or clinicians concerning dysfunction or underlying clinical issue [24, 26]. Analyzing variability in movement patterns allows for a better understanding of an individual's coordination. Some authors have suggested that variability in joint or segment coordination is essential during complex movements, providing flexibility to respond to stimuli and attenuate forces and impact shocks [25, 26].

Vector coding offers a method of measuring movement coordination and variability between two joints or segments at each point of a cyclic movement trial [24, 44], making it a viable framework for analyzing the cyclic rowing stroke sequence. An angle-angle diagram is constructed and vector orientation between consecutive time points is determined. Interpretation of the vector orientation is defined as in-phase motion, anti-phase motion, or motion completely in one segment. Hamill et al. [44] describes the angle-angle coordination diagram as represented

on a 0-360° range, and vector orientation points represent the segment in which the motion is occurring. These vector orientations on the angle-angle diagram are coupling angles. Motion is occurring in a single joint/segment when the coupling angle is 0°, 90°, 180°, or 270°, while the other joint/segment is fixed [44]. Equal, but directionally dependent, motion is occurring in both segments when the coupling angle is orientated at 45°, 135°, 225°, or 315°. However, movement is occurring in the same direction when coupling angle is 45° and 225°, but in opposite directions when the coupling angle is 135° and 315° [44].

In the study conducted by Needham et al. [24] a vector coding technique was utilized to analyze the lumbar-pelvic coordination during gait. This technique graphs tow segments at increasing walking velocities to show how the segments are moving relative to one another. Pelvic-trunk coordination at low walking speeds was shown to be in phase, and transitions to anti-phase at high speeds for a healthy population. However, participants experiencing low back pain had a reduced ability to transfer pelvic-trunk coordination from in-phase to anti-phase as walking speed increases. The preferred walking speed of the healthy participants was faster than the preferred walking speed for those suffering from low back pain.

In many of the rowing kinematic studies, the trunk segment was modeled as a single rigid segment. This is an invalid assumption because the spine is made up of 5 regions: cervical spine, thoracic spine, lumbar spine, sacrum, and coccyx. The 33 bones that make up these 5 regions have small degree's of movement between them, but allow for large range of motion of the entire spine [45]. Utilizing vector coding will help understand trunk segments movement relative to one another [24]. Interpreting coordination and variability of the pelvis-lumbar-thoracic motion throughout the rowing stroke sequence will give information on how rowing at increasing intensities influences intra-segmental coordination. Implementation of vector coding for

analyzing the rowing stroke sequence at varying intensities will allow for a better understanding of when the rower starts to deviate from the ideal technique. It will help provide further information about how rowing stroke intensity influences trunk coordination, and the athlete begin to break from the proper rowing form and focuses on getting their goal time.

The dynamical systems theory of motor control recognizes the overwhelming complexity required to perform a task. It is very useful for analyzing athletic performance and further explains the relationship between coordination and variability [25]. Rowing is a simple motion performed thousands of times, but efficient execution is complex. Utilizing the dynamical systems theory allows for analysis of variability within the rowing stroke at the different rowing intensities.

Conclusion

Low back pain is the most commonly reported injury in the sport of rowing. Training sessions are planned at varying intensities and are carried out for extended periods of time. As rower's become fatigued, they are less aware of their rowing posture and are at higher risk of developing lower back injuries due to the cyclic loading and unloading of the spine. While there have been several studies exploring how fatigue affects the rowing stroke sequence, no studies have been conducted exploring the intensity at which the rower deviates from proper form. Therefore, this study intends to observe the influence of rowing stroke intensity on thoracic-lumbar and lumbar-pelvis coordination. This study may identify the point at which the rower deviates from proper rowing form, which may provide an explanation for the increased prevalence of lower back injuries in collegiate rowing.

Chapter 3:

Methods

The purpose of this study was to observe the influence of rowing stroke intensity on thoracic-lumbar and lumbar-pelvis coordination. This study may identify the point at which the rower deviates from proper rowing form, which may provide an explanation for the increased prevalence of lower back injuries in collegiate rowing. This chapter describes the methods and all the equipment used during the testing protocol. Approval for the study was granted by the University of Tennessee, Knoxville Institutional Review Board prior to implementation of this study.

Participants

Participants for this study were recruited from the Volunteer's Varsity Women's Rowing team at the University of Tennessee at Knoxville. All participants were current members of the women's rowing team. A power analysis estimated that a sample size of 10 participants was needed to achieve adequate power for the study. This was based off of previous studies that measured maximum lumbar flexion angle during an incremental step-test [17, 46, 47]. Participants were between the ages of 18–25 years old. Rowers competing on the varsity rowing team at the time of the study were eligible to participate, provided they did not meet the exclusion criteria. Participants were not eligible to participate in the study if they had any major injuries to any part of the body, had ever received back surgery, missed one or more days of practice due to an injury within the previous 6-months, or self-scored low back pain greater than or equal to 3/10 on a ten-point scale the day of testing.

Experimental Protocol

The study was conducted at the University of Tennessee Knoxville Wayne G. Basler Boathouse and the University of Tennessee-Knoxville Biomechanics/Sports Medicine Laboratory. Participants reported to the boathouse or lab for one, 60-minute data collection session. The participants were asked to complete a questionnaire inquiring about their involvement with the sport of rowing, injuries incurred, practice missed as a result of the injury, etc. (Appendix 1).

Prior to the start of data collection, the researcher obtained information about the participant's fastest 2000-meter ergometer score from the previous season. Split-times were calculated for the targeted intensities, beginning at 70% intensity, and increased by 2.5% increments until 100%. Intensities were calculated from the total split-time in seconds, multiplied by a factor of the chosen intensity percentage to yield the new time in minutes per 500 meters.

$$70\%\ intensity = 1.3 * \left(total\ split\ time\ (\text{sec})\right)$$

$$= 70\%\ of\ 2000\ meter\ time$$

An example split intensity calculation for split-time of 1:47.0 min/500 meters is provided below:

1:47.0 (split-time) → 107.0 seconds (total time)

70% intensity = 1.3 * (107.0 sec)

70% goal split intensity = 140.0 sec (total time)

→ 2:20.8 min/500 meter (goal split-time)

Split intensities were chosen corresponding with a steady state rowing intensity and a maximal effort-sprint intensity. The 70% rowing intensity should be at a split the rower can maintain for long training bouts with ideal form [48]. The 100% rowing intensity was the average split intensity of the participants 2000-meter ergometer score from the previous season.

Upon completion of the forms and surveys, the participant changed in to a spandex unisuit, which is standard practice attire, and wore their personal training shoes. The participants completed a 5-minute warm up on the rowing ergometer, and were given adequate time for self-selected stretching.

Calibration of the IMUs was completed prior to placing the sensors on the participant. A calibration filter was applied to attenuate for distortions caused by ferrous metals and magnetic field interference in the data collection area. Magnetometer calibration was conducted using a figure oriented on the 3 axes (Figure 2). The researcher calibrated the IMU sensor by moving it in a figure eight pattern to map the points around the intersection point of the 3 axes, with the goal to make a complete sphere. A percentage determined how thoroughly the sensor was mapped through space to complete the sphere; each sensor needed to reach 90% or greater to ensure optimal calibration was achieved.

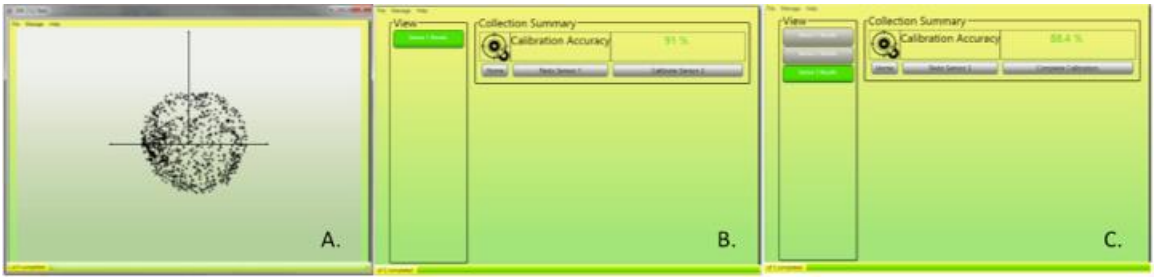

Figure 2. The figure above shows examples of the magnetometer calibration steps. A. shows a successful magnetometer calibration sphere. B. shows an example calibration accuracy estimate. C. shows what was considered an unsuccessful calibration accuracy estimate.

The next step in IMU sensor calibration was to calibrate the accelerometer property of each IMU sensor. The sensors were placed on a flat surface, side by side, and away from the computer system to avoid interference of ferrous metals or magnetic fields. Following the completion of

accelerometer calibration, a calibration file was saved and applied in to the last calibration step, initialize orientation filter. The system prompted the researcher to apply the calibration file when initializing the orientation filter, which prompted a running graph of the three sensors. Calibration was completed once the system had successfully initialized the orientation filter and the graphs converged. Magnetometer calibration, accelerometer calibration, and initializing orientation filter were completed for each individual sensor before proceeding to the next sensor calibration.

Three Delsys Trigno wireless inertial measurement unit sensors (IMUs) were placed using double-sided tape at the following locations:

- IMU sensor 1 was placed on the sacrum between the right and left PSIS.
- IMU sensor 2 was placed on the lumbar spine over L4 spinous process.
- IMU sensor 3 was placed on the thoracic spine over T7 spinous process between the participant's scapulae.

Following sensor placement, the participant stood in anatomical to zero the sensors, which defined alignment of the sensors and segments.

The participants were given time to familiarize themselves with the rowing equipment and practice rowing with the IMU sensors on. Sensors were checked to confirm they were securely attached and ensure placement would not interfere with the data collection. Participants performed an incremental step-test on the rowing ergometer to observe the influence of rowing stroke intensity on thoracic-lumbar and lumbar-pelvis coordination. The incremental step-test was performed at the targeted intensity for 30 strokes, followed by 30 seconds of rest before beginning the next split intensity. The step-test began at 70% intensity at 16 spm, and increased by 2.5% intensity until reaching 100% rowing intensity; stroke rate increased by 2 spm for every

5% increase in intensity. During the 30-second rest period, the participants continued rowing at a self-selected easy pace. An example incremental step-test is shown below in Table 1, which is based off an average 2000-meter split-time of 1:47.0 min/500 meters.

The rowing monitor screen displayed instant feedback for split-time and stroke rating following each stroke, which was also monitored by the researcher to ensure they were performing at the goal intensity. The participants were instructed to maintain the goal split-time and stroke rate at the given intensity and were permitted to deviate ±1 split second from goal intensity. If the participants deviated from the goal intensity for more than 2 stroke cycles, they had to re-do that split intensity at the end of the data collection.

Data were collected over the entire 30-strokes at each intensity. Once the participants reached their 100% stroke intensity, they were asked to attempt a maximal effort 30 stroke piece to assess rowing stroke kinematics during the sprint. An example of the incremental step-test is shown in the Table 1 below with split intensities and corresponding stroke rate.

Table 1. Example split-time breakdown based on average 2000-meter split-time of 1:47.0 min/500 meters.

Percent Intensity	**Stroke Rate (spm)**	**Total Split-Time (sec)**	**Split-Time (min/500 meters)**
70%	16	140.0	2:20
72.5%	16	137.0	2:17
75%	18	134.0	2:14
77.5%	18	131.0	2:11
80%	20	129.0	2:09
82.5%	20	126.0	2:06
85%	22	123.0	2:03
87.5%	22	120.0	2:00
90%	24	118.0	1:58
92.5%	24	115.0	1:55
95%	26	113.0	1:52
97.5%	26	110.0	1:50
100%	28	107.0	1:47
MAX_____.	MAX_____.	MAX_____.	1:38

Stroke rate is measured by calculating the time it takes to complete a single stroke.

$$Stroke\ Rate\ (SR) = \frac{60}{time\ per\ 1\ stroke\ (\text{sec})}$$

Instrumentation

The kinematics of the pelvis-lumbar-thoracic spine was measured throughout the rowing stroke sequence using EMMA software with Trigno wireless IMU sensors (Trigno, Delsys Inc., Natick, Massachusetts) sampled at 148 Hz. The step-test was conducted on the Concept II model D rowing ergometer (Concept Inc., Morrisville, Vermont), PM5 monitor. Macfarlane et al. [37] validated the Concept II rowing ergometer as a reliable piece of equipment to evaluate rowing performance. Prior to the start of each data collection, the drag factor and damper setting of the Concept II rowing ergometer were calibrated. Drag factor measures the flywheel's rate of deceleration. The rowing monitor calculates the work being done by using the drag factor and speed of the flywheel. The damper setting controls the amount of air permitted into the flywheel, 1= minimal resistance and 10 = maximal resistance. The flywheel's damper setting will be set to a resistance level 4, and the drag factor will be calibrated to 110 N m s^2.

Data Reduction and Analysis

Delsys EMMA software was used to calculate the orientation of each IMU sensor throughout the entire rowing stroke sequence. Data were collected for the entire 30-stroke sequences at each of the given intensities. Sensor orientations for each level of the incremental step-test were calculated using an XYZ Cardan rotation sequence (Sagittal-Frontal-Transverse) and exported for further analysis. The catch and the finish for each of the 30 stroke sequences were identified using a customized MATLAB (Mathworks, Inc., Natick, Massachusetts) script. One complete stroke sequence was defined as catch-finish-catch. The middle 10 stroke sequences were extracted from the 30 stroke sequences, as they best represented the true rowing

form at the given split intensity. The entire rowing stroke cycle was time normalized to 101 data points to allow for comparisons of rowing form between intensities. Peak lumbar flexion was used to define the catch position, and peak lumbar extension defined the finish position.

Thoracic-lumbar and lumbar-pelvis coordination was quantified using a vector coding technique described by Needham et al. [24]. Vector coding quantifies the continuous interaction of two segments by analyzing the vector orientation between the two consecutive data points on the angle-angle plot. The vector generated from the two segments interaction yields a coupling angle represented by a value between 0-360° relative to the right horizontal. The coupling angle details the vector orientation between two adjacent segments on an angle-angle diagram at one point in time [24, 27]. This study was interested in the coupling angle between the pelvic tilt and the lumbar flexion, and between lumbar flexion and thoracic flexion. Ideal rowing form was defined as an in-phase coordination pattern with an average coupling angle during the drive phase of 225° and 45° during the recovery phase. As there is limited research on rowing coordination and coordination analyses, these couplings were determined from pilot data and traditional kinematic research and reviews of the rowing stroke sequence. Equations for respective coupling angle were calculated for each instant (*i*) throughout each rowing stroke sequence using the proximal (*P*) and distal (*D*) segmental angles to calculate the coupling angle (γ_i) [24].

$$\gamma_i = \tan^{-1}\left(\frac{\theta_{D(i+1)} - \theta_{Di}}{\theta_{P(i+1)} - \theta_{Pi}}\right) * \frac{180}{\pi}$$

The coupling angle, γ_i, was then corrected to represent values between 0° and 360°

$$\gamma_i = \begin{cases} \gamma_i + 360 & \gamma_i < 0 \\ \gamma_i & \gamma_i \geq 0 \end{cases}$$

Due to the cyclic behavior of the rowing stroke sequence and the directional nature of the coupling angle, the following equations will be necessary to calculate average horizontal ($\bar{x}_i$) and vertical ($\bar{y}_i$) components at each instant (i), where n = the number of rowing stroke cycles.

$$\bar{x}_i = \frac{1}{\mathrm{n}}\sum_{i=1}^{n} \cos\gamma_i$$

$$\bar{y}_i = \frac{1}{\mathrm{n}}\sum_{i=1}^{n} \sin\gamma_i$$

The average coupling angle ($\bar{\gamma}_i$) was calculated from the average horizontal and vertical components at each instant:

$$\bar{\gamma}_i = \tan^{-1}\left(\frac{\bar{y}_i}{\bar{x}_i}\right) \cdot \frac{180}{\pi}$$

and corrected to represent values between 0° and 360°:

$$\bar{\gamma}_i = \begin{cases} \bar{\gamma}_i + 360 & \bar{\gamma}_i < 0 \\ \bar{\gamma}_i & \gamma_i \geq 0 \end{cases}$$

The average coupling angle length $\bar{r}\imath$ was calculated using the following equation:

$$\bar{r}_i = \sqrt{\bar{x}_i^2 + \bar{y}_i^2}$$

Coordination angle variability CAV_i was calculated using the following equation:

$$CAV_i = \sqrt{2 \cdot (1 - \bar{r}_i)} \cdot \frac{180}{\pi}$$

Statistical Analysis

To allow for stroke analysis, the entire rowing stroke was divided into drive and recovery phases. The drive phase was defined as the catch to finish position. The recovery phase was defined as extending from the finish to catch positions. Average thoracic-lumbar and lumbar-pelvis coupling angles for the drive and recovery phases were calculated for each participant to quantify coordination. Average coupling angle variability was also calculated for the drive and

recovery phases. Since coupling angle variability is known to increase at points of transition, average coupling angle variability was also calculated from the last 5% of the drive to the first 5% of the recovery (drive-recovery transition), and from the last 5% of the recovery to the first 5% of the drive (recovery-drive transition).

All statistical analyses were performed using SPSS (version 24, IBM Corporation, New York). For statistical analysis only the 70%, 80%, 90% and 100% split intensities were analyzed. A repeated measures ANOVA was utilized to determine differences between CA and CAV at the 70%, 80%, 90% and 100% split intensities. In the event of a significant ANOVA, post hoc pairwise comparisons were made between consecutive intensity levels (i.e., 70%-80%, 80%-90%, & 90%-100%) via independent paired t-tests.

Chapter 4:

Kinematic Analysis of Trunk Coordination Throughout the Rowing Stroke Sequence

Abstract

Rowing at the elite level requires proper sequencing of the rowing stroke so that the rower is able to produce an efficient stroke while minimizing injury risk. The cyclic motion of the rowing stroke sequence at low loads often results in overuse injuries, specifically in the lower back. Kinematic data of rower's pelvis-lumbar-thoracic spine were collected using inertial measurement sensors. An incremental step-test was conducted to observe the influence of increasing intensities on the lumbar-pelvis and lumbar-thoracic segments coordination and coordination variability. This study provides a new way of quantifying rowing kinematics using vector coding. The vector coding technique used in this study quantifies the relative motion and variability in lumbar-pelvis and thoracic-lumbar couplings during the rowing stroke. Rowers exhibited greater lumbar-pelvis coupling angle variability during the recovery-drive transition of the stroke sequence with increasing intensities, which may be necessary as the rower prepares for the added load applied when the oar is placed in the water. The findings from this study may also indicate that the low coupling angle variability during the drive and recovery phases of the rowing stroke may increase the demands placed on the lumbar and repeatedly stress the surrounding tissues, potentially explaining the cause of overuse injuries seen in the sport.

Introduction

Rowing is a physically demanding sport that is unique from many others because it requires the rower to have high aerobic endurance and muscular strength, while also being technically proficient. Training regimens are designed to develop the rower's muscular strength, aerobic and anaerobic endurance. Rowing training consists of a high volume of meters at a low intensity (65-85% max heart rate) to improve endurance [49, 50]. The remainder of their training focuses on developing their explosive power and anaerobic thresholds by doing high intensity interval training to improve the rower's sprinting. Rowers train extensively on the water in sweep (each rower has one oar) or scull (each rower has two oars) boats, and on the rowing ergometer, accumulating approximately 25 kilometers per training session.

The rowing stroke sequence (Appendix D, Figure 3) can be broken down into the catch position, drive phase, finish position, and recovery phase [1, 2, 51]. The catch position initiates the rowing stroke with the oar-blade entry into the water. Extension of the knees and ankles, followed by hip extension to extend the trunk defines the drive phase. The stroke is complete by drawing in of the arms towards the body. Once the oar-blade is out of the water the stroke is complete and the rower is in the finish position. The recovery phase is the reverse of the drive phase, and prepares the rower to take the next stroke.

Elite rowers have refined the simple rowing motion to optimize their technique to maximize the mean velocity of the entire system (boat, oar, rower) [18]. Rowing is a closed chain activity where the rower is constrained at the feet, seat, and handle, where the contact forces are imposed on the rower's body. Inability to execute the rowing sequence properly may influence the magnitude of loads transmitted at the lumbar-pelvis junction. Deviation from proper form results in a breakdown of power transmission through the kinetic chain,

consequently hindering performance and increasing potential risk of injury [18, 50]. Overuse, fatigue, poor technique, and repetitive flexion/extension have been suggested as contributing factors to lower back injuries in rowing [52].

Considering that rowing is a non-contact sport, the cyclic motion and long training sessions at low-moderate intensities may explain why chronic and overuse injuries are the most frequently reported injuries [7, 8]. Chronic and overuse injuries account for nearly 72% of all rowing related injuries [1, 2]. Lower back injuries represent 25% of all rowing overuse injuries, specifically occurring at the lumbar-pelvis joint and intervertebral discs.

The trunk travels throughout a large range of motion during the rowing stroke sequence, starting in 30° of flexion at the catch and finishing between 30-40° of extension at the finish. This large range of motion accounts for nearly 60% of the lumbar spine total range of motion [11, 13, 14]. Cadaveric studies measured the loading capacity of the vertebral column and tissues. The tissues were shown to undergo increased stress once lumbar flexion exceeded 50% of its available range of motion [15, 16].

Analyses have been performed in order to quantify the kinematics of rowing form, but oversimplify the trunk by representing it as a single rigid segment. Kinematic and kinetic analyses have been used to investigate the differences between good and poor technique that discriminate novice from elite rowers [46]. Other studies have measured the influence of fatigue on trunk kinematics during prolonged rowing, interval and high intensity rowing [12, 14, 34, 47, 53]. Lumbar range of motion was shown to significantly increase by 6° by the end of a prolonged 60 minute row [53]. Analysis of high intensity rowing has shown a decrease in lower extremity ROM, compensated for by an increased ROM at the lumbar-pelvis joint when comparing the kinematics of the initial and final trials of the test [17, 47]. Currently, no research

is available on segmental coordination during rowing, however, there are related coordination studies on cyclic lumbar-pelvis coordination during gait. Analysis of segmental coordination and coordination variability have been used in research and clinical settings to analyze cyclic movements like gait to potentially identify pathological abnormalities in gait patterns [24, 27]. Coordination and coordination variability analyses have been performed in clinical populations to assess the gait patterns of individuals with patellofemoral pain. These individuals showed reduced coupling angle variability in thigh rotations at heel-strike, in addition to increased variability in stride length [26]. The participants received treatment for patellofemoral pain and gait analyses data were recollected to compare the influence of pain on gait coordination and coordination variability. A 60% decrease in patellofemoral pain following treatment was accompanied with an increase in thigh rotation couplings at heel strike and decreased variability in stride length [26]. Variability in movement allows for a dispersion of the repetitive loads, which help to attenuate for the forces on a given joint.

As previously stated, lower back injuries are the most prevalent injury in the sport of rowing, most likely due to the long training sessions in combination with the repetitive loading and unloading of the lumbar spine at low-moderate intensities. However, it is still not known if rowing stroke intensity influences thoracic-lumbar and lumbar-pelvis coordination and coordination variability. Therefore, the purpose of this study was to observe the influence of rowing stroke intensity on thoracic-lumbar and lumbar-pelvis coordination and coordination using a vector coding technique. It was hypothesized that the rower's form (i.e. coupling angle) will begin to deviate from proper rowing form at the 90% split intensity. From pilot data and traditional rowing kinematic studies, ideal rowing form was defined using an in-phase coordination pattern and coupling angle of 225 during the drive phase and 45 during the recovery

phase. Additionally, we hypothesized that the variability in thoracic-lumbar and lumbar-pelvis spine couplings would increase as the rowing stroke intensity increases.

Materials and Methods

Participants

Ten healthy female rowers (age: 20.5±1.8 yrs, height 1.74±0.07 m, 68.57±6.2 kg) were recruited from the University of Tennessee-Knoxville Varsity Women's Rowing Team to participate in the study. Participants were between 18-25 years old, currently competing on the varsity team. Rowers were excluded if they had a history of back surgery, missed 1 or more days of practice due to an injury within the past 6 months, self-scored low back pain greater than or equal to 3/10 on a ten-point scale on the day of the study.

An *a priori* power analysis, using peak lumbar flexion angle results from previous research indicated that a total of 10 participants [17, 46, 47] were needed for an *alpha* of 0.05 and a *beta* of 0.80 using SPSS (version 24, IBM Corporation, New York, USA). All participants read and signed the informed consent document approved by the Institutional Review Board of the University of Tennessee, Knoxville. Upon completion of the informed consent, the participants answered a rowing questionnaire, which inquired about their involvement with the rowing and any injuries incurred while rowing.

Instrumentation

Kinematics of the pelvis-lumbar-thoracic spine was measured during data collection using three wireless Delsys EMMA inertial measurement unit (IMU) sensors (148 Hz, Trigno, Delsys Inc., Natick, Massachusetts). The Concept II model D (Concept Inc., Morrisville, Vermont) rowing ergometer with a PM5 monitor was used in the data collection. The

ergometer's damper was set to level four resistance, and the drag factor was calibrated to 110 N m s^2 prior to the start of each data collection.

Participants wore a spandex unisuit and were allowed to wear their personal training tennis shoes. The participants completed a 5-minute warm up on the rowing ergometer at a self-selected pace, and were given time for self-selected stretching. Three IMU sensors were placed on the sacrum between the right and left PSIS, the lumbar spine over L4 spinous process, and the thoracic spine between the scapulae on the spinous process of T7. Upon completion of sensor placements the participant stood in anatomical position to define the participants' neutral position.

Experimental Protocol

Data collections were conducted at the University of Tennessee Knoxville's, Wayne G. Basler Boathouse. The participants performed a graded exercise test, commonly referred to in rowing as an incremental step-test, at increasing intensities on the Concept II rowing ergometer. The step-test was designed to observe the influence of rowing stroke intensity on pelvis-lumbar-thoracic coordination. Targeted split intensities for the step-test were calculated prior to the start of the data collection and corresponded to percentages of the rowers previous seasons fastest 2000-meter average split-time. The 70% intensity was chosen corresponding to a steady state workload, while the 100% intensity was the equivalent of the rower's 2000-meter average split-time and would require maximal effort.

The incremental step-test was performed at the given intensity for 30 strokes, followed by 30 seconds of rest at self-selected pace before progressing to the next step in the test. The step-test began at 70% intensity at 16 spm, and increased by 2.5% intensity each step until reaching 100% intensity (Appendix C, Table 2). Stroke rating began at 16 spm and increased by 2 spm for

every 5% increase in intensity. A step was deemed unsuccessful if the participant failed to maintain the goal split-time for more than 2 consecutive stroke cycles.

Data Reduction and Analysis

Delsys EMMA software was used to calculate the orientation of each IMU sensor throughout the entire rowing stroke sequence. Data were collected for the entire 30-stroke sequences at each of the given intensities. Sensor orientations for each level of the incremental step-test were calculated using an XYZ Cardan rotation sequence (Sagittal-Frontal-Transverse) and exported for further analysis. The catch and the finish for each of the 30 stroke sequences were identified using a customized MATLAB (Mathworks R2015b, Inc., Natick, Massachusetts, USA) script. One complete stroke sequence was defined as catch-finish-catch. The middle 10 stroke sequences were extracted from the 30 stroke sequences, as they best represented the true rowing form at the given split intensity. Each rowing stroke sequence was time normalized to 101 data points.

Coordination was quantified using the vector coding techniques described by Needham et al. [24, 27]. Vector coding is a technique that measures the continuous interaction between two adjacent segments by measuring the vector orientation between two consecutive data points on the angle-angle diagram (Appendix G, Figure 11). This is known as the coupling angle and is represented by a value between 0-360° relative to the right horizontal. Due to the cyclic nature of coupling angle, the average coupling angle (CA) and coupling angle variability (CAV) across the middle 10 strokes were calculated using circular statistics [24]. This study was interested in the pelvic tilt and lumbar flexion, and between lumbar flexion and thoracic flexion segmental couplings. Ideal form was defined as an in-phase coordination pattern with a coupling angle of 225° during the drive phase, and 45° during the recovery phase.

Statistical Analysis

To allow for stroke analysis, the entire rowing stroke was divided into drive and recovery phases. The drive phase was defined as extending from the catch to finish position. The recovery phase was defined as extending from the finish to catch position. Average thoracic-lumbar and lumbar-pelvis coupling angles for the drive and recovery phases were calculated for each participant to quantify coordination (Appendix D, Figure 4). Average coupling angle variability was also calculated for the drive and recovery phases (Appendix D, Figure 5). Since coupling angle variability is known to increase at points of transition [26], average coupling angle variability was also calculated for the last 5% of the drive to the first 5% of the recovery (drive-recovery transition, DR), and from the last 5% of the recovery to the first 5% of the drive (recovery-drive transition, RD). Segmental coordination pattern and phase dominancy coupling angle values can be interpreted using the polar plot wheel provided (Appendix D, Figure 6).

All statistical analyses were performed using SPSS (version 24, IBM Corporation, New York). For statistical analysis only the 70%, 80%, 90% and 100% split intensities were analyzed. A repeated measures ANOVA was utilized to determine differences for CAs and CAVs at the 70%, 80%, 90% and 100% split intensities. In the event of a significant ANOVA, post hoc pairwise comparisons were made between consecutive intensity levels (i.e., 70%-80%, 80%-90%, & 90%-100%) via pair-wise comparisons.

Results

The performance results from the incremental step-test can be seen in Appendix C, Table 3 and Table 4 for thoracic-lumbar and lumbar-pelvis coupling angle and coupling angle variability. Statistical analyses were conducted using sample size of 10 participants, which still upheld the predicted power analysis. In Appendix D, Figure 7 and Figure 8 show average

thoracic-lumbar and lumbar-pelvis coupling angles, respectively, during the drive and recovery phase.

The results from the incremental step-test showed a significant change in lumbar-pelvis CAV during the recovery-drive transition (F= 3.324, p=0.035, $\eta_p^2 = 0.270$). The main effects for lumbar-pelvis during the recovery-drive transition showed that intensity significantly influenced variability between the 70%-80% intensity (Appendix C, Table 4). Lumbar-pelvis CAV (Appendix D, Figure 10) during the recovery-drive transition decreased from 12.5° to 7.5° between the70% and 80% intensities, respectively (p= 0.02). Lumbar-pelvis CAV increased from 80% to 100% intensity and showed a significant difference between the 80% intensity, 7.5°, and 100% intensity, 14.7° (p= 0.04). Lumbar-pelvis CAV during recovery-drive was approaching significance (p=0.066) between the 80% and 90% intensity. Lumbar-pelvis CAV across intensities was not significant during the drive-recovery transition (F = 0.048, p = 0.986, $\eta_p^2 = 0.005$), drive phase (F = 0.524, p = 0.669, $\eta_p^2 = 0.055$), or the recovery phase (F = 0.238, p = 0.869, $\eta_p^2 = 0.026$). There were also no significant changes across intensities for lumbar-pelvis CA during the drive phase (F = 1.484, p = 0.241, $\eta_p^2 = 0.142$) or the recovery phase (F = 0.708, p = 0.556, $\eta_p^2 = 0.073$).

Thoracic-lumbar CA (Appendix C, Table 3) (Appendix D, Figure 7) approached significance during the drive phase (F = 2.206, p = *0.110*, $\eta_p^2 = 0.197$) and the recovery phase (F = 2.345, p = 0.095, $\eta_p^2 = 0.207$). During the drive phase, thoracic-lumbar CA increased from 221.1° ± 11.3° at 70% intensity to 231.6° ± 21.7° at 80% intensity, and from 229.5° ± 24.0° at 90% intensity to 240.6° ± 36.8° at 100% intensity. Thoracic-lumbar CAV (Appendix D, Figure 9) did not significantly change with increasing intensities for the recovery-drive transition (F = 0.961, p = 0.425, $\eta_p^2 = 0.096$), drive-recovery transition (F = 0.083, p = 0.968, $\eta_p^2 = 0.009$),

drive phase (F = 0.625, p = 0.605, $\eta_p^2 = 0.065$), or recovery phase (F = 0.195, p = 0.899, $\eta_p^2 = 0.021$).

Discussion

Coordination analysis has previously never been done to quantify rowing form. Vector coding techniques have been applied to quantify coordination and coordination variability of other cyclic movements like gait kinematics [24, 26, 27]. The purpose of this study was to observe the influence of rowing stroke intensity on thoracic-lumbar and lumbar-pelvis coordination and coordination variability using the vector coding technique. It was hypothesized that the rower's form (i.e. coupling angle) would begin to deviate from proper rowing form at the 90% split intensity. The results of the current study do not support this hypothesis as there were no statistically significant changes in thoracic-lumbar or lumbar-pelvis CA as intensity increased throughout the step-test. We also hypothesized that the variability in thoracic-lumbar and lumbar-pelvis spine couplings would increase as the rowing stroke intensity increases. There was a significant difference in lumbar-pelvis CAV during the recovery-drive transition with increasing intensities. Specifically, lumbar-pelvis CAV decreased as intensity increased from 70% to 80%, and then increased as intensity increased from 80% to 90% and 100%, partially supporting our second hypothesis.

The closed-chain nature of rowing restricts the source of motion at the points of contact and prevents movement from being evenly distributed [18, 50]. The recovery phase of the stroke sequence prepares the rower's body to take the next stroke. Once the rower is at the catch position, he or she takes the stroke with their body situated in this position. The interaction between the seat and the pelvis restricts the amount of movement the pelvis is able to contribute to the stroke [47]. Similar restrictions are employed at the thoracic spine, as it is the connection

to the oar handle, the other point of contact for forces applied to the entire trunk. Ideal rowing form suggests that the back should remain flat so it can bear and distribute the load over the entire trunk segment [6, 33]. However, as the rower begins to fatigue, there is a breakdown in ideal form [53] which was defined in this study as an in-phase coordination pattern with average coupling angles of 225° during the drive phase and 45° during the recovery phase. This can cause one segment to move excessively compared to its coupled segment, altering the load distribution on the segments. This uneven distribution of the load may increase the potential for injury.

Lumbar-pelvis CA (Appendix C, Table 4) (Appendix D, Figure 8) during the drive phase in the sagittal plane predominantly exhibited an in-phase coordination pattern. The mean lumbar-pelvis coupling angle was approximately 212°, an in-phase coordination pattern, regardless of intensity level. This suggests that the relative motion of the lumbar was greater than relative motion of the pelvis during the drive phase. The mean lumbar-pelvis CA during recovery exhibited an in-phase coordination pattern at all intensity levels. While not significantly different, the coordination pattern was lumbar dominant at 70% intensity and became pelvis dominant as intensity reached 100%.

Mean lumbar-pelvis CAV (Appendix C, Table 4) (Appendix D, Figure 10) during the drive and recovery phases was low across the increasing intensities. The low variability in movement may be a reason for the increased demands on that joint, which can increase the risk of injury [26]. The variability in the lumbar-pelvis during recovery-drive transition showed greatest differences during the 70-80% intensity, and was approaching significance between the 80-90% intensity. This variability in movement at the catch position dictates where the initial stroke load is then dispersed during the drive. Preparation for the next stroke occurs in the

recovery phase of the rowing stroke sequence. Variability has been described as essential for joint coordination by allowing the individual to adjust to perturbations and react to stimuli[26]. Heiderscheit et al. [43] compared intra-limb joint coordination variability of individuals with patella-femoral pain to healthy participants during running and walking. They observed that individuals with patella-femoral pain had reduced joint CAV, of the injured limb, for thigh rotation coupling at heel strike compared to healthy individuals [43]. This may be important for rowing in that during the drive phase the thoracic-lumbar and lumbar-pelvis segments are under high loads while taking the stroke. The low variability in the lumbar-pelvis may increase the demands on the joint as the load is repeatedly stressing the same surrounding tissues. These repetitive loads may provide an explanation for the high occurrence of overuse injuries in collegiate rowing.

Mean thoracic-lumbar CA (Appendix C, Table 3) (Appendix D, Figure 7) during the drive and recovery phases increased as intensity increased, and coordination pattern was exhibited as in-phase. The segment of dominant movement changed from the thoracic segment at 70% intensity, to lumbar segment at 100% intensity. While there were no changes as intensity increased, thoracic-lumbar CAV was lowest during the drive and recovery phases (Appendix D, Figure 9). This finding was similar to that of the lumbar-pelvis CAV (Appendix D, Figure 10), which, as mentioned previously, may explain the high rate of lower back injuries in rowers.

This study was the first to address movement variability in the rowing stroke sequence at increasing rowing intensities. This paper presents a multi-segmented analysis of the trunk and related kinematic variability during the rowing stroke sequence from collegiate female rowers. The novel data from this study provide information for understanding thoracic-lumbar and lumbar-pelvis coordination and coordination variability during the rowing stroke sequence. The

repetitive motion of the rowing stroke sequence with low variability, coupled with the cyclic loading and unloading of the spine can be very harmful to the spinal structure and surrounding tissues. Furthermore, lumbar-pelvis CAV during the recovery-drive transition increased as intensity increased, which may be necessary for the rower to adjust to the added load incurred when the oar is placed in the water at the catch [26].

There are a number of limitations that must be considered when interpreting the results of the current study. Firstly, the split-time used when calculating intensity may not have been truly representative of the participant's maximum effort at 100% intensity. Intensities were calculated from the previous season's fastest 2,000-meter ergometer test average split-time. Therefore, the participant's fitness on the day of the test was likely to differ from our estimation of maximum effort. Secondly, it is difficult to maintain an exact split-time, as it is likely to change from stroke to stroke. This was controlled using the rowing monitor, which provides instant performance feedback on split-time and stroke rate, as well as having the researcher check the split-time on the monitor to ensure the targeted split-time is achieved. All participants successfully completed the targeted intensities of the incremental step-test. The rowers also are trained to maintain a certain split-time over an extended training session. Lastly, this study was limited to a sagittal plane analysis of flexion and extension. IMUs have been shown to be highly reliable for measuring sagittal plane rotations with moderate to low reliability in the frontal and transverse planes, respectively [54]

Further research is warranted to observe the coordination of individuals with back pain or history of injury to healthy individuals. Furthermore, a longitudinal study to document pelvis-lumbar-thoracic CA and CAV in elite rowers may inform researchers whether the rower developed an injury from over use, or if their form was poor which lead to development of the

injury. Such a longitudinal study would also aid in establishing CAV threshold for the optimal level of variability throughout the rowing stroke. Finally, comparing the differences in coordination and coordination variability for ergometer rowing to rowing on the water would help better understand the influence of spinal rotation on trunk coordination.

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Appendices

Appendix A: Informed Consent

INFORMED CONSENT

Kinematic Analysis of Trunk Coordination Throughout the Rowing Stroke Sequence

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Introduction

You are invited to take part in a research study entitled "Kinematic Analysis of Trunk Coordination Throughout the Rowing Stroke Sequence". The purpose of this study is to investigate the effects of rowing stroke intensity on pelvis-lumbar-thoracic spine coordination (i.e. rowing form during steady state versus maximal intensity) of collegiate level rowers. Please ask the principal investigator (PI) to explain any words, information, or study protocol that you do not clearly understand. Before consenting to participate in this study, it is important that you read and understand the study in its entirety, and potential risks and benefits.

Eligibility

To participate in this study you must be between the ages of 18-25 years old. You must be a current member of the Tennessee Varsity Rowing Team. You must NOT have undergone back surgery at any point. Lastly, you may not have suffered an injury within the last six months resulting in one or more days of missed practice.

Experimental Protocol and Duration:

You will be asked to attend one biomechanical test session, which will be conducted at the University of Tennessee's, Wayne G. Basler Boathouse or the University of Tennessee Biomechanics Laboratory. The testing session is anticipated to take 60 minutes to complete. During the testing session, baseline measurements of height, weight, and age will be recorded. You will then complete a rowing questionnaire inquiring about your involvement with the sport, related injuries, and your personal best 2,000-meter split-time from the previous season.

Upon completion of the baseline measurements and rowing questionnaire, you will be given 5 minutes to warm up on the rowing ergometer at a self selected pace, followed by self selected stretches. Once you are warmed up, three Delsys Trigno wireless inertial measurement unit sensors (IMUs) will be placed using double-sided tape at the following locations:

- IMU sensor 1 will be placed on the sacrum at waistband level.
- IMU sensor 2 will be placed on the lumbar spine over L4.
- IMU sensor 3 will be placed on the thoracic spine between the scapulae

Your previous seasons personal best 2,000-meter split-time will be used to calculate rowing intensity throughout the step-test. The step-test will include 30 strokes on goal split, followed by 30 seconds of rest before beginning the next intensity. The step-test will begin at 70% intensity and increasing by 2.5% until reaching 100% intensity. An additional MAX effort trial will be collected following the 100% intensity. Stroke rate will be controlled and will increase by 2 spm

for every 5% increase in intensity. You must maintain the goal split for the given intensity and can only deviate by ± 1 split second, and ±1 spm for stroke rate. The trial will be considered unsuccessful if you fail to maintain those parameters and that intensity will be re-collected at the conclusion of the step-test. Below is an example step-test based on a 2,000-meter split-time of 1:47.0 min/500 meters:

Percent Intensity	Stroke Rate (spm)	Total Split-Time (sec)	Split-Time (min/500 meters)
70%	16	140.0	2:20
72.5%	16	137.0	2:17
75%	18	134.0	2:14
77.5%	18	131.0	2:11
80%	20	129.0	2:09
82.5%	20	126.0	2:06
85%	22	123.0	2:03
87.5%	22	120.0	2:00
90%	24	118.0	1:58
92.5%	24	115.0	1:55
95%	26	113.0	1:52
97.5%	26	110.0	1:50
100%	28	107.0	1:47
MAX	MAX	MAX	1:38

Potential Risks:

You will be performing an incremental step-test starting at steady state intensity, increasing by 2.5% until reaching 100% intensity. An additional trial to observe rowing form during a MAX effort split-time and stroke rate will conclude the data collection. You will be required to warm up for 5 minutes on the rowing ergometer; followed by self-selected stretching to minimize risk of injury. Potential risks of participating in this study are minimal and level of exertion is similar to that experienced in a normal practice.

Some skin irritation may result from the adhesive properties of the double-sided tape used to place the sensors on the skin. These are known risks associated with adhesive tap on the IMU sensors, however, the likelihood of this risk is low.

Loss of confidentiality is a possible risk of participating in the study. Such a disclosure may link you to your participation in the study. Although there are steps in place to prevent a breach in confidentiality, it is a still a risk associated with the study.

Benefits:

This study may provide further explanation for the increased prevalence of lower back injuries among collegiate rowers. It may provide information about the demands placed on the trunk segment during strenuous activity. It will also provide a more accurate representation of trunk kinematics.

Participation and Withdrawal

Participation in this study is entirely voluntary. You have the right to refuse to participate at any point throughout the data collection process with no penalty or consequences to you the

participant. You are encouraged to ask any and all questions throughout the data collection process about anything that is unclear or you do not understand.

Confidentiality:

Your identity will be held in the highest of confidence and all information obtained throughout the data collection process will be kept confidential. You will receive an identification number that only you and the PI know; this number will be used on all forms and data collection sheets. All forms and data will be kept in a password protected computer and a locked filing cabinet in the Biomechanics Lab (Room 136). Only the PI and faculty advisor will have access to the documents. If the study is published in a scientific journal or book, all participant information will remain confidential and they will NOT be identified in any way.

Contact Information:

If you have any questions or would like additional information about the study, or are experiencing adverse effects, please contact McDaragh Minnock, at mminnock@vols.utk.edu or call (865) 974-2091, or Dr. Joshua Weinhandl, PhD at jweinhan@vols.utk.edu or call (865) 974-9556. If you have any questions about your rights as a participant, please contact the University of Tennessee Knoxville IRB Compliance Office at utkirb@utk.edu or (865) 974-7697.

Consent Statement

I have read the above information and the study has been explained to me and my questions have been answered. I have received a copy of this form and I agree to participate in the above study as described.

Participant's Name (Print): _____

Participant's Signature_____Date:_____

Investigator's Signature_____Date:_____

Appendix B: Rowing Questionnaire

Rowing Questionnaire

Participant ID Number_____.

1. D.O.B. _____Height_____Weight_____.
2. At what age did you begin rowing? _____.
3. Sweep or scull? _____.
4. Port or starboard? _____.
5. Have you ever suffered a back injury from rowing? Explain.
6. Do you experience more back pain during certain activities? Explain.
7. Did you have to modify training due to back injury? Explain.
8. How many training sessions were missed from back injury? Explain.
9. What is your pain level on a daily basis?

	0	1	2	3	4	5	6	7	8	9	10
No Pain		Low	-	-	-	-	-	-	-	-	High

10. What is your current level of pain?

	0	1	2	3	4	5	6	7	8	9	10
No Pain		Low	-	-	-	-	-	-	-	-	High

11. After what type of training do you experience the most back pain? Explain.
12. How have you modified your stroke to reduce back pain?

Appendix C: Tables

Table 2. Example split-time breakdown based on average 2000-meter split-time of 1:47.0 min/500 meters.

Percent Intensity	**Stroke Rate (spm)**	**Total Split-Time (sec)**	**Split-Time (min/500 meters)**
70%	16	140.0	2:20
72.5%	16	137.0	2:17
75%	18	134.0	2:14
77.5%	18	131.0	2:11
80%	20	129.0	2:09
82.5%	20	126.0	2:06
85%	22	123.0	2:03
87.5%	22	120.0	2:00
90%	24	118.0	1:58
92.5%	24	115.0	1:55
95%	26	113.0	1:52
97.5%	26	110.0	1:50
100%	28	107.0	1:47
MAX	MAX	MAX_____.	1:38

Table 3. Mean and standard deviations of thoracic-lumbar coupling angle and coupling angle variability (degrees).

	Coupling Angle		***Coupling Angle Variability***			
	Drive	**Recovery**	**Recovery-Drive**	**Drive**	**Drive-Recovery**	**Recovery**
70%	221.1±11.3	39.7±10.8	12.5±8.0	6.1±9.4	22.3±12.8	6.3±6.2
80%	231.6±21.7	51.4±23.1	16.4±14.2	6.2±6.6	22.4±11.7	6.1±4.9
90%	229.5±24.0	50.8±24.2	14.4±13.8	3.7±2.5	21.0±13.0	5.7±4.0
100%	240.6±36.8	57.0±39.3	14.2±11.3	5.8±6.9	22.8±17.5	6.6±6.5

Table 4 Mean and standard deviations of lumbar-pelvis coupling angle and coupling angle variability (degrees).

	Coupling Angle		***Coupling Angle Variability***			
	Drive	**Recovery**	**Recovery-Drive**	**Drive**	**Drive-Recovery**	**Recovery**
70%	215.4±8.8	40.0±14.5	12.5±10.0 *	12.5±10.7	22.1±12.5	7.5±8.8
80%	212.5±8.6	41.7±10.5	7.5±7.4	14.1±7.9	22.5±14.12	7.5±7.4
90%	212.1±6.8	45.3±15.2	12.8±12.7	15.8±4.6	23.2±15.8	8.1±8.1
100%	210.5±10.1	47.6±16.6	14.7±13.7 *	16.3±9.9	22.9±16.3	8.7±7.5

** Indicates significant difference from 80% intensity* ($p < 0.05$).

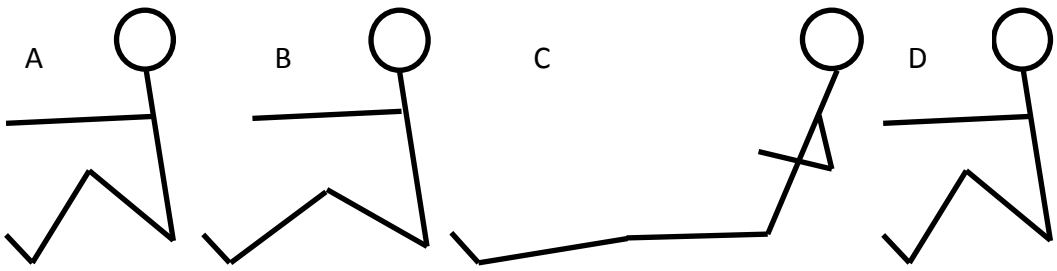

Figure 3. The rowing stroke sequence starting with the catch (A), followed by the finish (C) and subsequent catch (D). The drive phase is initiated at the catch and is concluded at the finish (A-C). The recovery phase is initiated at the finish position and concludes at the catch position of the next stroke (C-D).

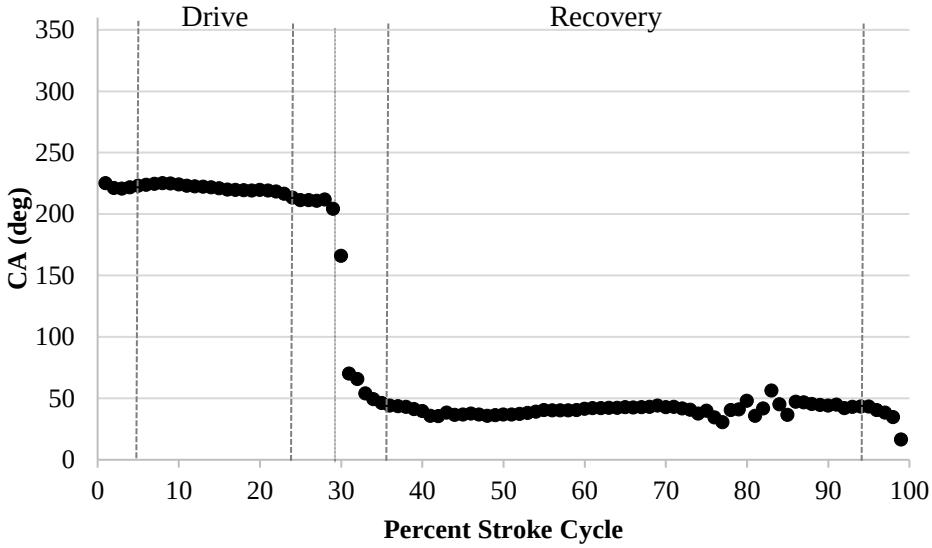

Figure 4. Mean thoracic-lumbar coupling angle for a representative participant.

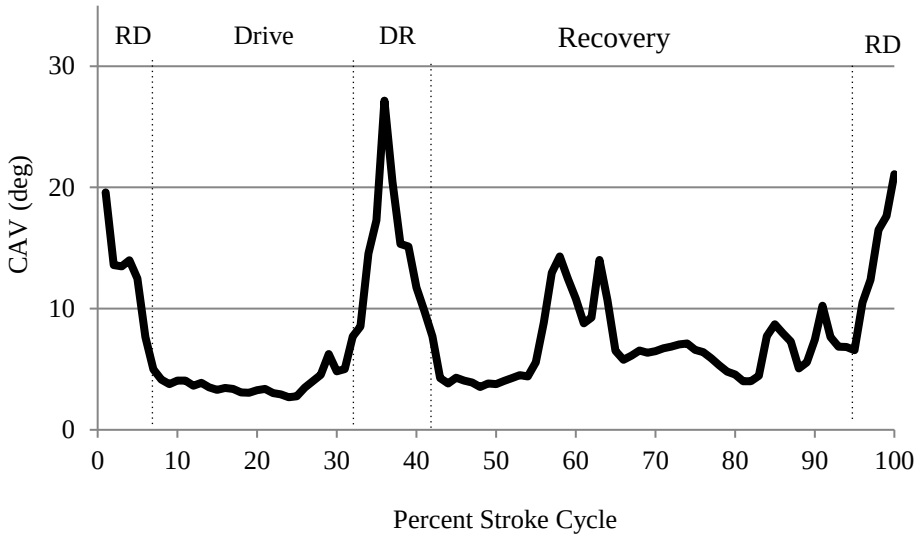

Figure 5. Mean thoracic-lumbar coupling angle variability for a representative participant during the drive and recovery phase, as well as recovery-to-drive (RD) and drive-to-recovery (DR) transitions.

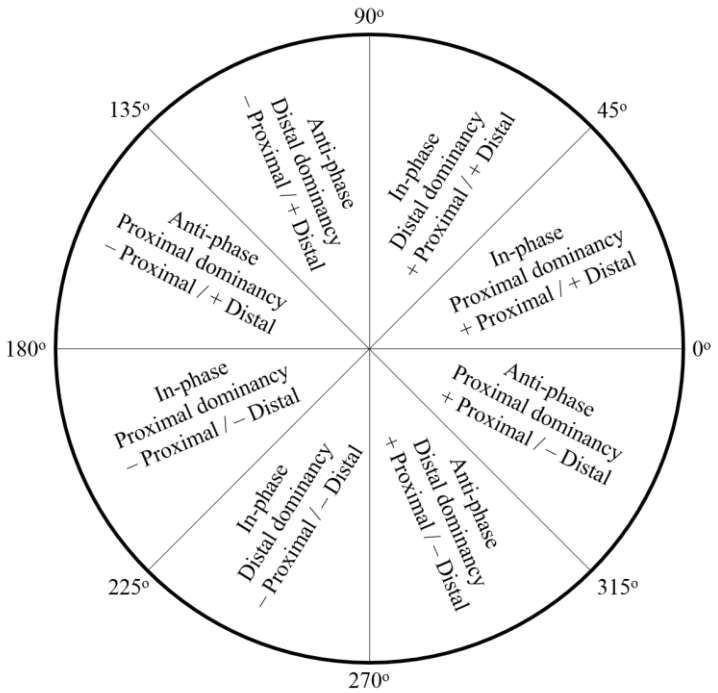

Figure 6. Polar plot to represent segmental coordination pattern and segmental dominancy for the proximal and distal segments at specific coupling angles (deg).

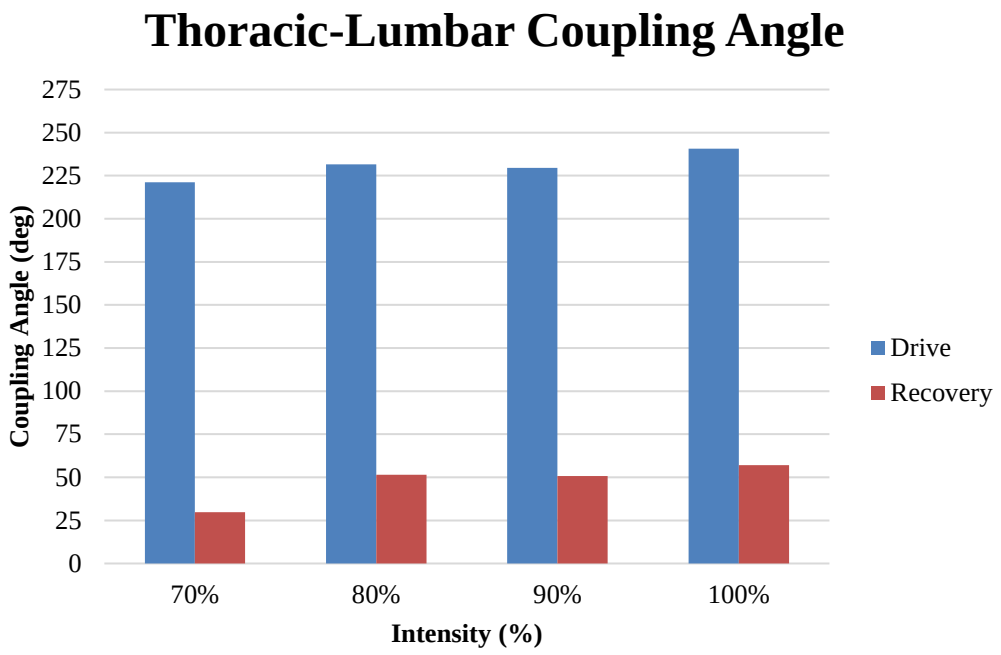

Figure 7. Average thoracic-lumbar coupling angle during the drive phase (blue bars) and recovery phase (red bars).

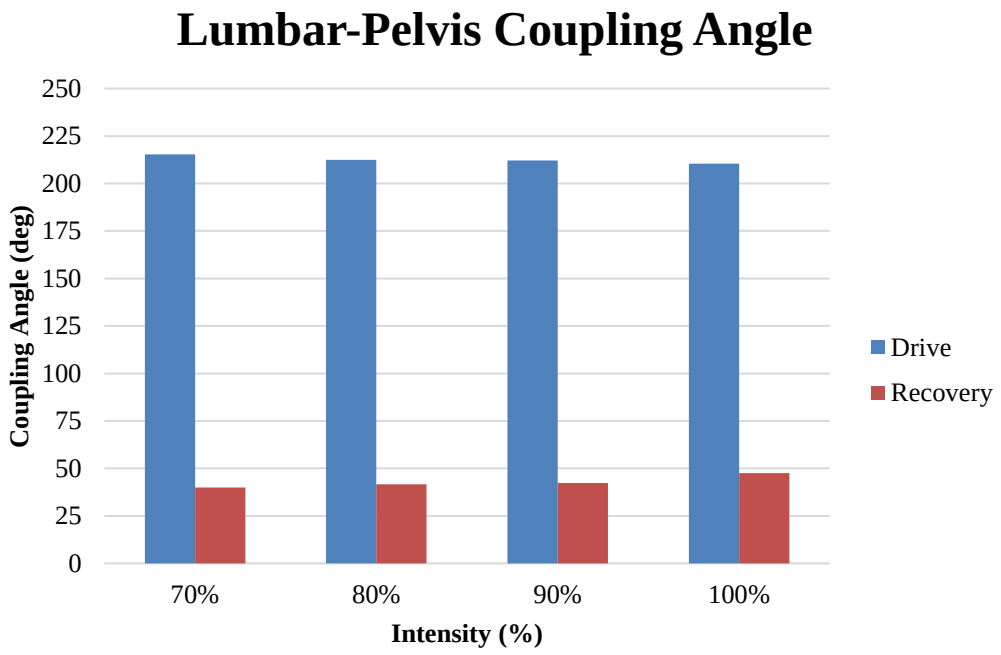

Figure 8. Average lumbar-pelvis coupling angle during the drive phase (blue bars) and recovery phase (red bars).

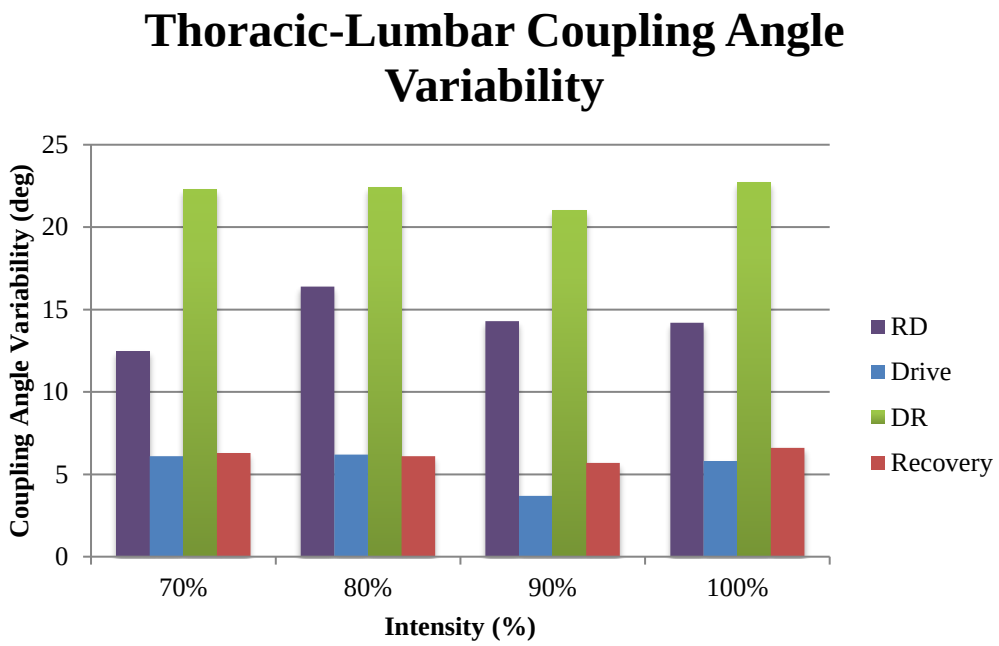

Figure 9. Mean thoracic-lumbar coupling angle variability (deg) for the recovery-drive transition (RD), drive phase, drive-recovery transition (DR) and recovery phase at the four rowing split intensities of interest.

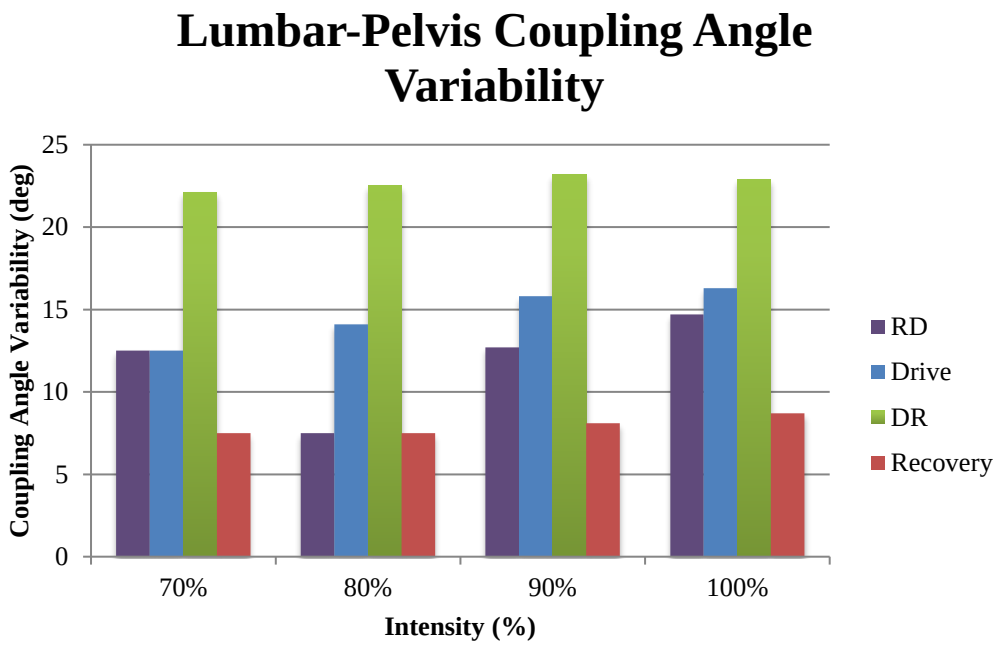

Figure 10. Mean lumbar-pelvis coupling angle variability (deg) for the recovery-drive transition (RD), drive phase, drive-recovery transition (DR) and recovery phase at the four rowing split intensities of interest. There was a significant difference in the lumbar-pelvis CAV during the RD transition at the 70% and 100% intensity from 80% intensity ($p<0.05$).

Appendix E: Participant Demographics

Table 5. Participant demographic information on age, height, mass, 2,000-meter ergometer time from the previous season, and corresponding average split-time.

Participant Demographics					
Participant	*Age (yrs)*	*Height (m)*	*Mass (kg)*	*2,000m Time (min)*	*Average Split-time (min/500m)*
S01	25	1.68	63	7:28.0	1:52.0
S02	21	1.75	66.6	7:27.0	1:51.5
S03	19	1.748	79.4	7:08.6	1:47.1
S04	19	1.79	74	7:05.0	1:46.2
S05	20	1.77	71.6	7:23.0	1:50.7
S06	19	1.8	74.8	7:26.0	1:51.5
S07	20	1.63	61.2	7:30.8	1:52.7
~~*S08*~~	~~24~~	~~1.79~~	~~68~~	~~7:30~~	~~1:52.5~~
S09	20	1.7	63.5	7:24.0	1:51.0
S10	20	1.7	63	7:46	1:56.5
S11	22	1.88	68.6	7:27	1:51.7
~~*S12*~~	~~19~~	~~1.67~~	~~60.5~~	~~7:48.0~~	~~1:57.0~~
Means and STDV	20.5±1.8	1.74±0.07	68.±6.2	7:24.5±0:11.4	1:51.1±0:02.9

Appendix F: Individual Participant Results

Table 6. Mean thoracic-lumbar CA (deg) during the drive phase of the stroke cycle for each participant at the given intensities. Includes means and standard deviations for the participants at the given intensities.

Thoracic-Lumbar Coupling Angle During the Drive (deg)				
Participant	*70%*	*80%*	*90%*	*100%*
S01	221.41	221.78	222.02	221.18
S02	219.85	217.78	220.01	225.27
S03	223.80	216.57	217.11	216.81
S04	217.41	216.54	214.62	213.13
S05	219.49	224.07	215.88	219.40
S06	215.88	212.93	212.31	215.18
S07	231.53	245.25	245.14	264.28
S09	243.54	275.25	292.01	289.00
S10	219.08	223.78	224.00	224.11
S11	199.13	262.09	232.19	317.86
Means and STDV	221.1±11.3	231.6±21.7	229.5±24.0	240.6±36.8

Table 7. Mean thoracic-lumbar CA (deg) during the recovery phase of the stroke cycle for each participant at the given intensities. Includes means and standard deviations for the participants at the given intensities.

Thoracic-Lumbar Coupling Angle During the Recovery (deg)				
Participant	*70%*	*80%*	*90%*	*100%*
S01	32.01	33.05	33.75	35.21
S02	40.17	39.58	39.07	42.99
S03	40.15	38.14	39.20	39.61
S04	34.46	34.10	32.35	31.52
S05	34.76	34.75	30.80	32.07
S06	31.95	60.68	58.23	28.49
S07	52.95	68.12	70.96	87.34
S09	59.56	91.53	104.06	103.06
S10	23.75	29.59	31.16	29.21
S11	46.90	84.66	68.08	140.70
Means and STDV	29.7±10.8	51.4±23.1	50.8±24.2	57.0±39.3

Table 8. Mean thoracic-lumbar CAV (deg) during the recovery-drive transition phase of the stroke cycle for each participant at the given intensities. Includes means and standard deviations for the participants at the given intensities.

Thoracic-Lumbar Coupling Angle Variability During the Recovery-Drive (deg)				
Participant	*70%*	*80%*	*90%*	*100%*
S01	6.54	4.34	3.29	3.67
S02	4.93	7.63	6.19	4.44
S03	12.12	7.08	8.60	9.30
S04	6.05	4.79	5.45	5.18
S05	20.49	26.52	13.63	25.58
S06	24.39	44.99	48.22	31.38
S07	8.25	12.91	15.61	25.82
S09	16.69	24.80	18.78	10.39
S10	2.68	1.90	1.39	1.44
S11	22.44	29.13	22.31	24.50
Means and STDV	12.5±8.0	16.4±14.2	14.3±13.8	14.2±11.3

Table 9. Mean thoracic-lumbar CAV (deg) during the drive phase of the stroke cycle for each participant at the given intensities. Includes means and standard deviations for the participants at the given intensities.

Thoracic-Lumbar Coupling Angle Variability During the Drive (deg)				
Participant	*70%*	*80%*	*90%*	*100%*
S01	2.28	1.63	1.19	1.00
S02	2.43	2.41	2.05	1.83
S03	2.76	2.13	1.93	2.33
S04	2.43	1.92	2.10	1.64
S05	4.42	21.34	3.28	17.36
S06	4.14	5.60	6.92	5.15
S07	2.00	3.44	5.14	4.16
S09	5.71	8.15	6.42	4.26
S10	1.86	1.30	1.02	0.91
S11	32.53	13.69	7.16	19.70
Means and STDV	6.1±9.4	6.2±6.6	3.7±2.4	5.8±6.9

Table 10. Mean thoracic-lumbar CAV (deg) during the drive phase of the stroke cycle for each participant at the given intensities. Includes means and standard deviations for the participants at the given intensities.

Thoracic-Lumbar Coupling Angle Variability During the Drive-Recovery (deg)				
Participant	*70%*	*80%*	*90%*	*100%*
S01	8.29	6.06	7.16	4.29
S02	13.65	10.39	11.28	4.13
S03	16.66	21.07	28.46	36.44
S04	37.00	18.02	13.77	8.24
S05	19.02	34.59	10.73	34.98
S06	27.85	35.43	45.41	25.84
S07	16.03	18.53	27.69	24.25
S09	20.60	31.14	23.52	23.22
S10	13.76	10.71	7.12	7.57
S11	50.53	38.01	34.73	58.50
Means and STDV	22.3±12.8	22.4±11.6	21.0±13.0	22.7±17.5

Table 11. Mean thoracic-lumbar CAV (deg) during the recovery phase of the stroke cycle for each participant at the given intensities. Includes means and standard deviations for the participants at the given intensities.

Thoracic-Lumbar Coupling Angle Variability During the Recovery (deg)				
Participant	*70%*	*80%*	*90%*	*100%*
S01	2.00	1.88	1.85	1.28
S02	4.64	3.99	3.35	3.85
S03	5.63	3.33	3.21	2.99
S04	10.13	3.76	3.29	3.66
S05	2.63	4.97	2.06	9.40
S06	5.08	8.31	9.82	7.12
S07	2.14	4.14	9.86	5.53
S09	5.45	9.97	6.47	4.06
S10	2.89	2.65	3.82	4.40
S11	22.48	18.24	13.58	24.11
Means and STDV	6.3±6.2	6.1±4.9	5.7±4.0	6.6±6.5

Table 12. Mean lumbar-pelvis CA (deg) during the drive phase of the stroke cycle for each participant at the given intensities. Includes means and standard deviations for the participants at the given intensities.

Lumbar-Pelvis Coupling Angle During the Drive (deg)				
Participant	*70%*	*80%*	*90%*	*100%*
S01	220.21	219.49	219.47	219.36
S02	219.52	216.16	215.07	200.39
S03	216.06	217.94	217.25	218.91
S04	220.46	220.8	222.03	224.27
S05	205.26	201.28	200.65	205.02
S06	209.28	213.7	209.03	208.42
S07	199.28	194.68	202.99	196.82
S09	219.03	219.91	212.54	199.28
S10	214.5	212	209.9	210.62
S11	230.1	209.1	211.95	222.12
Means and STDV	215.4±8.8	212.5±8.6	212.1±6.8	210.5±10.1

Table 13. Mean lumbar-pelvis CA (deg) during the recovery phase of the stroke cycle for each participant at the given intensities. Includes means and standard deviations for the participants at the given intensities.

Lumbar-Pelvis Coupling Angle During the Recovery (deg)				
Participant	*70%*	*80%*	*90%*	*100%*
S01	39.50	39.61	39.06	38.99
S02	41.05	35.52	37.82	61.32
S03	33.03	38.18	38.84	38.93
S04	40.60	40.28	42.00	42.46
S05	30.18	32.03	33.29	44.73
S06	32.62	63.11	61.17	79.52
S07	24.61	58.43	80.68	62.18
S09	38.21	39.23	33.34	18.84
S10	42.19	37.54	35.44	46.98
S11	78.09	32.71	51.40	41.80
Means and STDV	40.0±14.5	41.7±10.5	42.3±15.2	47.6±16.5

Table 14. Mean lumbar-pelvis CAV (deg) during the recovery-drive transition phase of the stroke cycle for each participant at the given intensities. Includes means and standard deviations for the participants at the given intensities.

Lumbar-Pelvis Coupling Angle Variability During the Recovery-Drive (deg)				
Participant	*70%*	*80%*	*90%*	*100%*
S01	6.23	1.10	3.01	4.07
S02	3.92	3.21	3.60	5.39
S03	5.93	4.43	5.30	4.83
S04	4.64	3.05	3.19	3.55
S05	26.10	7.21	18.45	37.06
S06	26.78	20.27	42.96	36.93
S07	4.42	5.40	11.24	16.25
S09	8.93	4.74	17.45	10.01
S10	10.44	3.34	2.25	3.20
S11	27.30	22.12	20.02	25.87
Means and STDV	12.5±10.0	7.5±7.4	12.7±12.7	14.7±13.7

Table 15. Mean lumbar-pelvis CAV (deg) during the recovery phase of the stroke cycle for each participant at the given intensities. Includes means and standard deviations for the participants at the given intensities.

Lumbar-Pelvis Coupling Angle Variability During the Recovery (deg)				
Participant	*70%*	*80%*	*90%*	*100%*
S01	1.65	1.10	1.07	0.94
S02	3.04	3.21	2.73	6.23
S03	4.76	4.43	4.08	3.09
S04	11.74	3.05	2.73	2.51
S05	5.99	7.21	6.98	15.06
S06	6.51	20.27	23.58	15.62
S07	3.42	5.40	7.16	6.83
S09	2.03	10.83	15.71	8.02
S10	2.88	4.74	3.90	4.07
S11	4.03	3.34	6.33	7.67
Means and STDV	7.5±8.8	7.5±7.4	8.1±8.1	8.7±7.5

Table 16. Mean lumbar-pelvis CAV (deg) during the drive-recovery transition phase of the stroke cycle for each participant at the given intensities. Includes means and standard deviations for the participants at the given intensities.

Lumbar-Pelvis Coupling Angle Variability During the Drive-Recovery (deg)				
Participant	*70%*	*80%*	*90%*	*100%*
S01	13.62	9.68	10.72	7.45
S02	10.06	8.18	9.70	10.69
S03	16.75	16.25	24.24	26.81
S04	33.48	13.67	21.88	12.19
S05	23.38	41.58	13.80	43.93
S06	28.18	36.64	44.41	27.66
S07	12.39	12.07	19.12	16.23
S09	18.63	21.86	22.75	16.14
S10	13.73	17.86	8.83	10.87
S11	50.60	47.26	56.82	57.09
Means and STDV	22.1±12.5	22.5±14.1	23.2±15.8	22.9±16.3

Table 17. Mean lumbar-pelvis CAV (deg) during the recovery phase of the stroke cycle for each participant at the given intensities. Includes means and standard deviations for the participants at the given intensities.

Lumbar-Pelvis Coupling Angle Variability During the Recovery (deg)				
Participant	*70%*	*80%*	*90%*	*100%*
S01	1.65	1.10	1.07	0.94
S02	3.04	3.21	2.73	6.23
S03	4.76	4.43	4.08	3.09
S04	11.74	3.05	2.73	2.51
S05	5.99	7.21	6.98	15.06
S06	6.51	20.27	23.58	15.62
S07	3.42	5.40	7.16	6.83
S09	2.03	10.83	15.71	8.02
S10	2.88	4.74	3.90	4.07
S11	4.03	3.34	6.33	7.67
Means and STDV	7.5±8.8	7.5±7.4	8.1±8.1	8.7±7.5

Appendix G: Coupling Angle Example

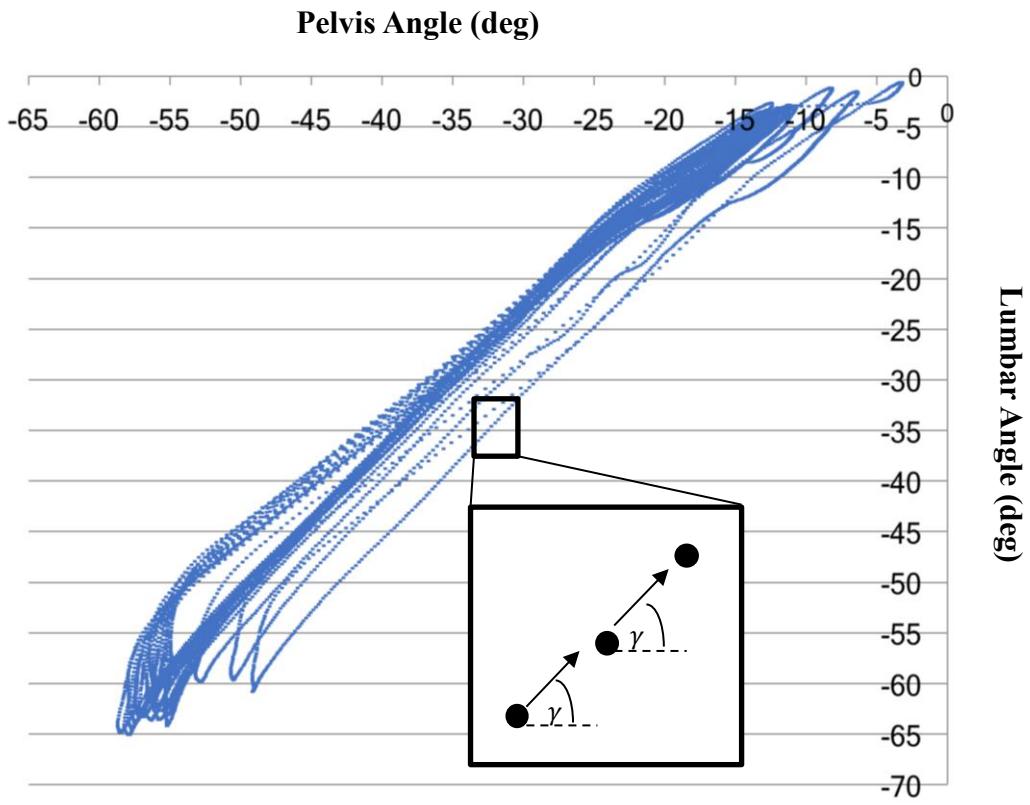

Figure 11. Example graph of lumbar-pelvis angle-angle diagram to show how an average coupling angle is determined using the vector orientation of each data point throughout time.

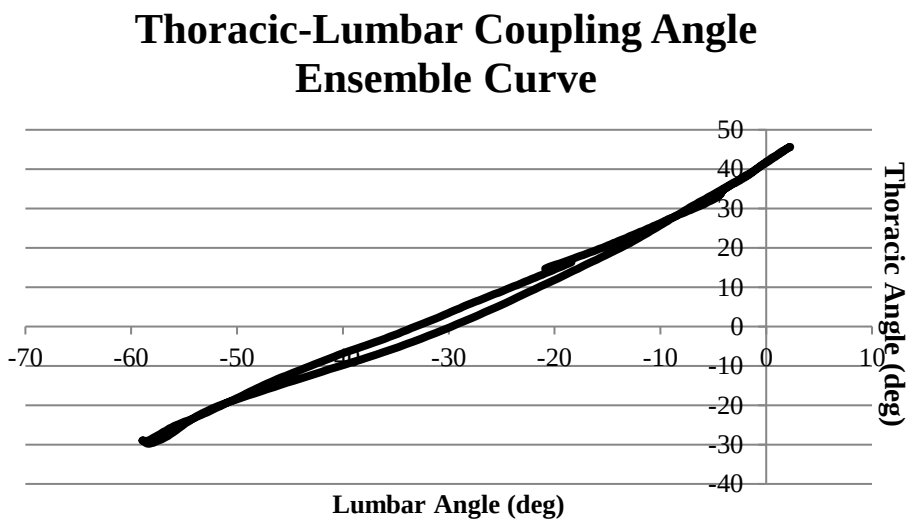

Figure 12. Ensemble curve of mean thoracic-lumbar coupling angle for one subject at the 70% intensity level.

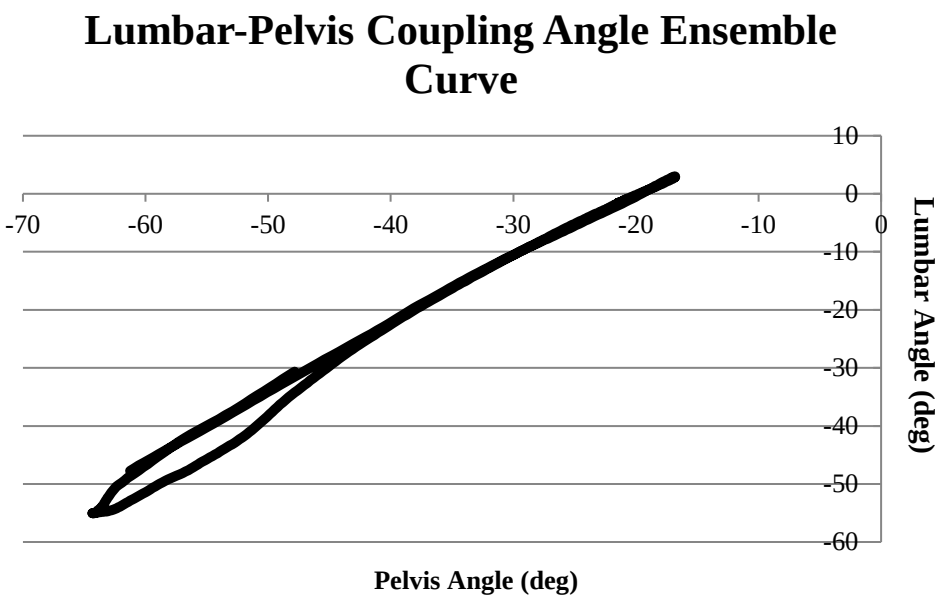

Figure 13. Ensemble curve of mean lumbar-pelvis coupling angle for one subject at the 70% intensity level.

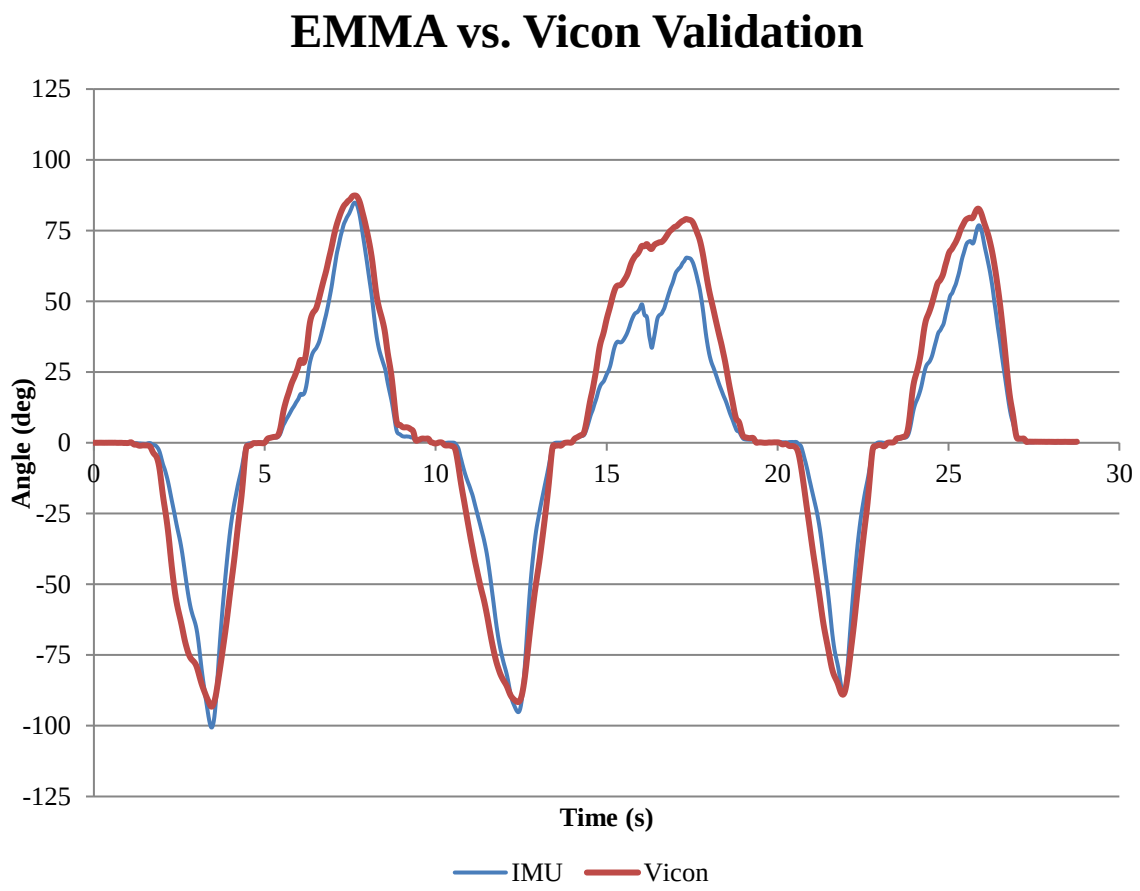

Figure 14. System validation. Sagittal plane, flexion-extension movements, to verify using EMMA IMUs in this study against a traditional motion capture system (Vicon Motion Analysis, Inc., Centennial, CO, USA). Delsys Trigno IMU sensors were attached to semi-rigid thermo plastic plates to collect traditional motion capture data using Vicon. The IMU and plate were manually moved through flexion and extension movements to collect sagittal plane movement data. A custom Matlab (Mathworks, Inc., Natick, Massachusetts, USA) function was written to match the Vicon sampling frequencies to the Delsys Trigno systems to accurately compare the curves. The average difference between IMUs and Vicon was 2.07° during this motion.

Vita

McDaragh Rose Minnock was born in Pittsburgh, Pennsylvania to the parents of Mary C. Minnock and Tom Minnock. She is the third of four daughters, Brianna, Mary, and Noreen. She attended Pine-Richland High School in suburbs of Pittsburgh, Pennsylvania. After graduating from high school she headed to the Volunteer's state, Tennessee, where she attended the University of Tennessee, Knoxville. During her time in university, she competed on the Volunteer's Varsity Women's Rowing Team. She was recognized as a member of the Big XII all conference First Team in 2015 and 2016, and also earned SEC academic honors and Big XII academic honors. She earned her Bachelors of Science degree from the University of Tennessee, Knoxville in May 2015 in Kinesiology. She accepted a graduate teaching assistantship within the Office of Information Technology at the University of Tennessee-Knoxville, while pursuing a Masters of Science degree in Kinesiology with a concentration in Biomechanics.