COORDINATION OF SWIMBENCH FREESTYLE IN ELITE AND NON-ELITE SWIMMERS: A DYNAMICAL SYSTEM APPROACH

Tracy H. Spigelman
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COORDINATION OF SWIMBENCH FREESTYLE IN ELITE AND NON-ELITE SWIMMERS: A DYNAMICAL SYSTEM APPROACH

ABSTRACT OF DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Exercise Science in the College of Education at the University of Kentucky

By
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Dr. David R. Mullineaux, Assistant Professor of Kinesiology and Health Promotion
Lexington, Kentucky
2009
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ABSTRACT OF DISSERTATION

COORDINATION OF SWIMBENCH FREESTYLE IN ELITE AND NON-ELITE SWIMMERS: A DYNAMICAL SYSTEM APPROACH

Elite swimmers can be distinguished from novice swimmers by freestyle stroke technique. Elite swimmers move through multiple coordination modes, increases in stroke lengths, stroke rates, and body roll allowing for a more symmetrical stroke and increased speed compared with novice swimmer during 100m freestyle.

Coaches strive to improve swimmers’ performance by providing feedback about stroke technique, mostly from the pool deck where view of the full stroke cycle is obstructed by the water. Tools to assess swimming are often expensive and require extra training, which does not provide a pragmatic solution. A dryland rotational swimbench would provide a means to evaluate freestyle swimming. The aim of the present study is to evaluate the sensory motor system of elite and novice level swimmers by comparing kinematic, coordinative structures and spatial-temporal characteristics of freestyle stroke on a dryland swimbench with a rotational component.

Thirty elite and novice collegiate and masters swimmers were instrumented with reflective markers bilaterally on the upper extremity and torso. A series of four ten second trials of freestyle sprint swimming were performed on the swimbench. Repeated measures were used for statistical analysis for comparison between and within groups. Bonferroni corrections were used as post-hoc analysis.

Results indicated no significant difference between elite and novice swimmers’ sensory-motor system, kinematics or spatio-temporal systems on a rotational swimbench. Similarities could be accounted for by swimmers perceiving a novel task due to differences in sensory feedback, and mechanical limitations of the bench. It is noteworthy that catch-up/opposition coordination are more common than superposition which provides support for the swimbench providing a more similar representation to in water swimming.
KEYWORDS: Dynamical systems; freestyle swimming, kinematics, rotational swimbench; sensory motor system
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DISSERTATION

Tracy H. Spigelman

The Graduate School
University of Kentucky
2009
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DEDICATION

This dissertation is dedicated to my mom who always believed in me and instilled in me the knowledge that I could do anything I wanted as long as I was willing to work hard enough for it.
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This dissertation wouldn’t have been completed without the mentorship, guidance and friendship of Tim Uhl, David Mullineaux, and Dr. Shapiro. Guidance and advice was also provided by Dr. Nitz, who helped with fine-wire EMG in the early mornings to collect pilot data.

Special thanks go to my family. My dad, Mike, my sister Betsy, my brother Brett and his family, and my Aunt Patti and Uncle David and cousin Rebecca who provided love and emotional support through this doctoral program, and who understand what this degree means to me. Also, thank you to the rest of my cousins who cheered me on through the doctoral process, and to Dot- Dot and Pop-Pop, I love you both.

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Chapter One

Introduction

Dynamic systems theory suggests that the ability of the sensory-motor system to re-organize and fine tune a coordinated movement pattern occurs in response to the specific task constraints of a goal driven activity [1-3]. Traditionally, this theory is tested in controlled environments using simple finger pointing tasks [4], but recently it has been used to explain differences in more complex movement tasks as seen in athletics [5]. The basis of the theory is that the sensory motor system can account for contextual variability. Contextual variability refers to the notion that with each movement made, the environmental, and mechanical constraints impact the following movements and are continuously adjusted through the sensory motor system [6]. Researchers agree that in competitive freestyle swimming, elite and novice swimmers can be differentiated by their specific stroke characteristics. It is suggested that elite swimmers better adjust their stroke technique by increasing stroke length or stroke rate during the last 50m of a 100m freestyle a race to win, whereas novice swimmers continue to use the same stroking technique for all 100m [7,8]. The ability to view these differences on land could have beneficial implications for coaching. Limited research has tested the sensory motor system of elite and novice swimmers to determine whether stroke characteristics seen in the water can be replicated in a non-aquatic environment with similar contextual cues, such as on a dryland swimbench with a rotational component [9,10].

Elite freestyle swimmers are distinguished by increased stroke lengths [11,12], stroke rates, and body roll [2,13-17]. Elite swimmers also refine their coordination modes to include a greater amount of time in the propulsive phase compared to non-elite swimmers [18]. This is reflected in the index of coordination (IdC), which measures the percentage of lag time between propulsive phases of each stroke cycle, and has been used to categorize a swimmer’s stroke technique. Categories are: super-position coordination, where the duration of the propulsive phase is greater than the duration of the recovery
phase for each stroke cycle; catch-up coordination, where there is a lag in time between the beginning of propulsion phase; and opposition coordination where the duration of the propulsive phase is equal to the duration of the recovery phase [2,19]. Swimmers transition through coordination modes during a race until they reach a steady state; elite swimmers use stroke technique closer to superposition whereas novice swimmers tend to remain in a catch-up/opposition coordination [19]. Elite swimmers tend to maintain a more symmetrical stroke compared with novice swimmers [20,21] to allow them to generate forces evenly as they swim and maintain a faster velocity [20]. If the same technique differences could be viewed on land as well as in the water, it may offer support for coaching swimming technique in varying environments providing coaches with alternate methods to provide specific feedback to swimmers.

Freestyle stroke length and stroke rate can be easily observed by a coach standing on the pool deck; however, the pulling motion of the arm under the water can not be observed easily. Since the pulling motion of the arm affects the stroke length, focus on stroke technique includes in water drills which cue swimmers to increase stroke length and stroke rate [22-24]. While these drills are helpful, it is difficult for coaches to evaluate if the drills are being performed correctly due to the water obscuring the view. To compensate for this the majority of instruction comes from coaches demonstrating arm technique from the pool deck or the coach will move the swimmer’s arm through the stroke motion while the swimmer is standing on the pool deck. In both cases the swimmer is receiving coaching feedback from outside of the water, where resistive feedback from the water that may provide important cues for hand placement during the stroke is absent.

There is a need for a land based coaching tools to better evaluate the bilateral nature of freestyle and provide sensory feedback similar to the contextual constraints of the water during the pulling phases of the stroke. Swimbenches traditionally limit motion at the trunk and provide resistance in only two-dimensions [10,25]. Past research showed elite swimmers did not receive the sensory feedback to replicate their natural in water stroke on these
swimbenches [10]. Newer swimbenches allow rotation on the cranial-caudal axis and provide varying amounts of resistance during the freestyle stroke [9]. These capabilities may provide elite swimmers with the sensory feedback to replicate their freestyle technique in water. If so, it would allow coaches to better evaluate the differences between swimmers of varying skill levels during the propulsive phase of freestyle to provide appropriate feedback to swimmers. It is currently unclear if the motor control pattern and kinematics of the freestyle stroke can be replicated on a dryland swimbench with a rotational component.

The aim of the present study is to evaluate the sensory motor system of elite and novice level swimmers by comparing kinematic, coordinative structures and spatial-temporal characteristics of freestyle stroke on a dryland swimbench with a rotational component.

Statement of the Problem

Dynamical systems theory suggests that the sensory motor system provides continuous feedback based on constant changes in the context of a movement [1,26,27]. Previous research shows that in the water elite swimmers can adjust stroke technique to swim faster whereas novice swimmers do not [28]. Limited information is known evaluating the role of the sensory motor system if the environment is altered. If elite swimmers demonstrated superior stroke technique in a dryland environment over a novice cohort, it would support the idea that swimmer’s sensory motor systems adapt at varying rates according to skill level. This type of information could be used for performance enhancement, and would support the swimbench as a tool to evaluate stroke technique.

Coaching swimming is challenging because the propulsive phase of the freestyle stroke difficult to evaluate from the pool deck. Some pools have underwater windows, video systems and even 3-dimentional panning periscopes to evaluate swimming technique. These systems are rare, costly and do not allow coaches to provide direct contact during instruction. A land based coaching tool that provide more realistic sensorimotor cues similar to water could be helpful if skill level differences commonly seen in water were present on a dryland apparatus. Measurement of the kinematics, coordination and spatial
temporal differences between novice and elite swimmers would support that a dryland swimbench can replicate sensorimotor demands in a different but more coachable environment.

**Purpose**

The purpose of the present study is to evaluate the sensory motor system of elite and novice level swimmers by comparing kinematic, coordinative structures and spatial-temporal characteristics of freestyle stroke on a dryland swimbench with a rotational component to determine if differences exist between the sensory motor systems of elite and novice swimmers.

**Research Hypothesis**

Aim 1. To distinguish coordination characteristics of elite and novice level swimmers on a rotational swimbench.

Hypothesis 1a: Elite level swimmer will transition from a catch-up to super-position freestyle stroke mode during the third and fourth trial of a 100m freestyle on the swimbench.

Hypothesis 1b: Novice level swimmers will remain in a catch-up freestyle stroke mode for all four trials of the 100 freestyle on the swimbench.

Aim 2. To compare upper extremity kinematics between elite and novice level swimmers on a rotational swimbench.

Hypothesis 2a: Elite level swimmers will demonstrate greater displacement of the hand and elbow in the cranial/caudal, medial/lateral, and vertical directions than novice swimmers.

Hypothesis 2b: Elite level swimmers will demonstrate greater body roll compared to novice level swimmers.
Hypothesis 2c. Elite level swimmers will demonstrate a more symmetrical stroke pattern compared to novice level swimmers.

Hypothesis 2d: Elite level swimmers will demonstrate medial-lateral hand velocities similar to those reported in the literature.

Aim 3. To determine if elite swimmers upper extremity spatial-temporal characteristics on a rotational bench simulate those in water as reported in the literature.

Hypothesis 3a: Elite level swimmers will demonstrate stroke lengths similar to those reported in the literature.

Hypothesis 3b. Elite level swimmers will demonstrate stroke rates similar to those reported in the literature.

Significance of the Study

There is a gap in the literature describing how the sensory motor system in swimmers of varying skill levels provides feedback when the environments change. Theoretically, if the sensory motor system of the elite swimmers has greater adaptability, the same differences should be seen in elite and novice swimmers on the dryland rotational bench as in the water. Results of this study will provide insight about how the sensory motor system in elite and novice level swimmers adapt to dryland swimbench, which could have applications for improving coaching techniques.

Limitations

- The swimbench was a prototype and unable to handle the forces placed on it by elite level male swimmers. As such, swimmers were required to perform between 70-80% of their maximum speed for a 100 freestyle.
• Swimmers reported difficulty maintaining a smooth rotational movement while on the swimbench. This may have altered how they performed their freestyle stroke.

• The swimbench had a stationary torso pad which allowed for rotation around the cranial-caudal axis, but prevented translation in the cranial-caudal direction. This limitation had two implications. First, swimmers could not incorporate a glide phase in their freestyle stroke which decreased the length of the stroke cycle by eliminating the catch phase. Second, the freestyle stroke typically consists of four phases of the stroke: catch, pull, push, and recovery [13]. Catch phase occurs during the forward glide of the swimmer. Since swimmers were stationary on the swimbench, a glide was not possible, thus catch phase was omitted from the data analysis. The stroke cycle was defined as pull, push, and recovery. This is discussed in further detail in the kinematics section of the discussion, Chapter 5.

• Elastic tubing was used as the resistive mechanism resulting in resistive forces during both the propulsive and non-propulsive phases. In the water, the majority of resistive forces occur during the propulsive phase from the interaction of the water and arm [17,29]. During non-propulsive phases, while swimming in water, the resistive forces from the interaction of the air and the arm are less than during the propulsive phase [30]. On the swimbench the elastic tubing provided resistance for both the propulsive and non-propulsive phases which could have resulted in decreased stroke lengths. This is discussed in more detail in the kinematics section of the discussion in Chapter 5.

Delimitations

• In water data were not captured, thus there is no direct comparison of the swimmers’ stroke on land and in the pool. Since historical research [10,25] has suggested improving a swimbench by incorporating a long axis rotational component, the present study is based on this suggestion.
Swimbench data were compared with historical data of elite level swimmers during the propulsive phase of freestyle swimming [11,12]. Novice technique was compared to literature in current coaching and swimming journals.

In the water, forward movement results from swimmers taking advantage of the active drag forces by using a sculling motion (side to side motion) of the hand during the pull through. As the hand is shaped similar to a foil, when it moves through the water, pressure gradients are formed resulting in increased lift forces perpendicular to the motion of the hand [31], which help move the body in a forward direction to propel the swimmer through the water. The swimbench allowed for resistance in two dimensions only, cranial/caudal and vertical. Previous research has documented this limitation [25]. Active drag on the swimbench was adjusted by the amount of resistance for each participant based on his or her speed (Appendix A).

Data analysis of freestyle stroke typically uses the water surface as a reference for defining the phases of the stroke [32]. In the absence of water, the C7 marker was used as a reference point since it was closest to the surface of the water and remained fairly stationary throughout the stroke trials.

**Operational Definitions**

This section provides definitions for commonly used terminology in the manuscript in alphabetical order. For the majority of the terms two definitions are presented. The first definition (1) is the definition used in the current research with respect to in water swimming. The second definition (2) is the definition used specific to rotational swimbench.

**Body-roll Angle (BR):** The angle between the line connecting the two posterior shoulder markers (the shoulder axis) and the cranial-caudal axis (x/y) [33].
**Catch Phase:** The moment the hand enters the water to when the arm begins a backward motion [32].

**Central Nervous System (CNS):** Brain and spinal cord [34].

**Cranial-Caudal elbow displacement on the swimbench ($E_{dc}$):** Mean linear displacement of the elbow relative to a fixed reference, C7, in the cranial-caudal direction during the propulsive phase.

**Cranial-Caudal hand displacement on the swimbench ($H_{dc}$):** Mean linear displacement of the hand relative to C7 in the cranial-caudal direction during the propulsive phase.

**Contextual constraints:** 1) Task, environmental and organic demands placed on the body during everyday activities [6]. 2) Swimming stroke performed (i.e. freestyle), the arm motion both in and out of the water, and anthropometrics of the individual performing a swimming stroke [2].

**Coordinative structures:** 1) A proposed strategy used by the central nervous system (CNS) for controlling the numerous degrees of freedom in the body that suggests muscles are functionally linked to perform an activity as a single unit [6]. 2) Freestyle swimming requires an opposing cyclic motion of both arms which includes controlling degrees of freedom at the shoulder, elbow, and hand. The redundancy of the CNS coordinates the motion at these three joints to perform the freestyle swimming arm motion [2].

**Dynamical systems:** A theory proposed by Bernstein [27] to explain how the CNS plans and performs volitional movement. The main focus is that task, organism, and environmental constraints affect the sensory-motor system’s ability to spontaneously and continuously refine motor output. Once a motor output occurs, the afferent feedback results in a further refinement of a movement. This is a continuous process as volitional movements are performed [1,3,6,26].

**Elite swimmer:** Swimmer with the ability to perform 100m freestyle race at or faster than 75% of a national record swimming time [35].

**Freestyle Swimming:** Overarm or front crawl stroke [13].
Federation Internationale de Natation (FINA): International governing body of swimming.

Index of Coordination (IdC): An equation developed by Chollet et al [19] to quantify the arm motions of the competitive stroke in swimming.

\[
\text{IdC} (%) = \frac{((t_{\text{pull1}} - t_{\text{exit1}}) + (t_{\text{pull1}} - t_{\text{exit2}})) / 2}{t_{\text{sc}}} \times 100 \quad [19]
\]

The IdC is the percentage of the stroke cycle where \( t_{\text{pull1}} \) is the time of the first right arm pull, \( t_{\text{exit1}} \) is the time of the first left arm exit, \( t_{\text{pull1}} \) is the time of the first left arm pull, \( t_{\text{exit2}} \) is the time of the second right arm exit, and \( t_{\text{sc}} \) is the time of the total stroke cycle. The IdC has been validated with the three following freestyle stroke coordination modes:

**Catch-up mode:** There is a negative lag time between arms, or the percentage of the stroke cycle the arms are in a non-propulsive phase is greater than in the propulsive phase (IdC<0%). These values have been shown to range from -0.9±5.4 to -11.9±4.2 [15] for a 100m freestyle. The right arm is in entry phase while the left arm is in recovery phase. This mode is commonly reported in non-elite swimmers and in elite swimmers in the beginning of a long distance swimming race [19].

**Opposition mode:** There is no lag time between arms in this stroke mode because the arms are at extreme opposition (IdC =0%). This coordination is difficult to achieve and has not actually been reported in the literature, however it is believed that higher level swimmers progress through an opposition mode as they increase velocity. Elite swimmers move through this phase as the sensory-motor system is adjusting itself to move into a superposition mode [19].

**Superposition mode:** There is a positive time lag between arms, or the percentage of time the arms are in propulsive phase is greater than the amount of time in the non-propulsive phase (IdC>0%). These values range from 0.3±2.0 [15] to 2.53±4.4 [19] for elite swimmers. The first right arm is in pull phase while the left arm is in the end of the push phase, hence both arms are in propulsive phases. Elite level swimmers are seen to use this stroke mode in sprint races less than 100 m [19].
Medial-Lateral elbow displacement on the swimbench ($E_{dml}$): Mean linear displacement of the elbow relative to C7 in the medial-lateral direction during the propulsive phase.

Medial-Lateral hand displacement on the swimbench ($H_{dml}$): Mean linear displacement of the hand relative to C7 in the medial-lateral direction during the propulsive phase.

Medial-Lateral Velocity on the swimbench ($H_{vml}$): Rate at which the hand moves in the medial-lateral direction during the propulsive phase on the swimbench.

Novice swimmer: A swimmer with the ability to perform 100m freestyle below 74% of the world record swimming time [35].

**Pull Phase:** 1) Begins when the arm begins a backward motion to when it is perpendicular to the body [32]. 2) Begins at the end of the catch phase as the 3rd metacarpal-phalangeal (MCP) joint begins a backward and downward motion and ends as the when the 3rd MCP joint is in line with the vertical axis moving in a positive direction.

**Push Phase:** 1) Begins when the arm is perpendicular to the body to when the third metacarpal phalangeal (MCP) joint exits the water [32]. 2) Begins at the end of pull phase as the 3rd MCP joint continues moving backwards and starts moving in an upward direction until the 3rd MCP joint crosses the cranial-caudal direction while changing from a negative to positive direction.

**Recovery Phase:** 1) Begins when the hand exits the water and ends when it reenters the water [32]. 2) Begins at the end of push phase and continues until the beginning of pull phase.

**Sensory motor system:** Afferent nerve fibers that carry sensory motor signals to the cortex of the brain and efferent nerve fibers that carry a response to the signal.

**Stroke length (SL):** 1) The distance (m) that the hand or body travels in a cranial-caudal direction from the time the hand enters the water to the point that it leaves the water [12,19,36]. 2) The range of hand displacement (m) in the cranial-caudal direction ($H_{dcc}$) while on the rotational swimbench.
**Stroke rate (SR):** 1) The time (s) for the hand to travel from entry into the water to reentry the water divided by 60 [37]. 2) The number of stroke cycles per second (c/s) of a swimmer while on the rotational swimbench.

**Swimming velocity:** Stroke length multiplied by stroke rate [2,19,35].

**Upward-Downward elbow displacement on the swimbench (E_{ud}):** Mean linear displacement of the elbow relative to C7 in the upward-downward direction during the propulsive phase.

**Upward-Downward hand displacement on the swimbench (H_{ud}):** Mean linear displacement of the hand relative to C7 in the upward-downward direction during the propulsive phase.
Chapter Two

Review of Literature

Introduction

The purpose of this study is to evaluate the sensory motor systems of elite and novice level swimmers to determine if they can be differentiated on a rotational swimbench. It is hypothesized that elite swimmers have more dynamic sensory motor system compared to novice swimmers that will allow them to use the same stroke technique on the rotational swimbench as in the water. This review of literature is intended to explain a possible motor control rationale for the variations in skill level, and then to apply the theory to a new coaching tool. The review is divided into three sections. Section one addresses the properties of fluids and biomechanics of freestyle. Section two addresses the differences in freestyle swimming stroke technique between elite and novice swimmers and then provides a motor control theory to explain possible differences in skill levels. Coaching swimming presents a number of challenges, as the majority of the stroke is performed under the water. Section three reviews technology used to evaluate freestyle swimming and the challenges associated with these tools. This section also provides insight about the use of a dryland rotational swimming bench as a means of evaluating and correcting stroke technique based on the motor control theory discussed in section II.

Section I

Fluid Dynamics

To fully realize the complexity of coaching swimming it is important to understand the properties of water and how it interacts with the swimmer. This section will provide a brief description of fluid dynamics with respect to a swimmer. Buoyancy, lift and drag forces are explained. This information is then applied to the biomechanics of freestyle swimming.
Knowledge about the force of the water on the swimmer is broken into basic concepts and published in coaching magazines for practical application [18,22-24]. Placement of the hand into the water, the path traveled by the hand once it enters the water, and the coordinated roll of the body during a stroke cycle are usually the main focus of coaches. By focusing on these points, coaches are teaching swimmers to decrease the resistive forces of the body relative to the water. For example, coaches stress a technique called streamlining, where body position is straight, following a start or flipturn because the shape of the swimmers body affects the amount of resistance on the swimmer [13]. Researchers who have studied elite level swimmers have noted that elite swimmers who had greater body mass generated less resistive drag than novice swimmers who were smaller [29]. Decreased resistance was attributed to technique of the elite swimmers which can be adjusted to improve performance by manipulating the forces of the water.

There are two primary forces that impact swimming. These are buoyant forces and drag forces. Buoyancy is defined by Archimedes principle. It states the magnitude of the buoyant force acting on a given body is equal to the weight of the fluid displaced by the body [38].

\[ FB = VD \gamma \]  

\text{Equation 0.1}

Where \( F_B \) is the buoyant force, \( V_D \) is the volume of the fluid displaced by the body, and \( \gamma \) is the specific weight of the body. Buoyancy is influenced by the mass and density of the swimmer and by the density, specific weight, and viscosity of the water. A body's center of buoyancy is the point through which buoyant forces act. For a body to float in a swimming pool, the amount of fluid displaced should be equal to the weight of the body. Also, the center of buoyancy through the body must be in line with the gravitational force. For competitive swimming, buoyancy is believed to create a slight advantage by allowing the swimmer to achieve a higher body position in the water.
Drag is defined as a force that resists any motion of a body through a fluid [38]. A fluid is any substance that tends to flow or continuously deform when acted upon by a shear force (e.g. air and water). Both passive and active drag forces have been defined in the water. Passive drag forces refer to how the water acts on a stationary swimmer [39]. Much of this research has been done by towing swimmers through the water, and do not provide realistic insight to the water forces on the swimmer as they swim. Active drag forces refer to resistance that occurs as the swimmer acts on the water [17,29,39-42]. The equation for drag force is:

\[ F_D = \frac{1}{2} C_D \rho A_p v^2 \]  

\textbf{Equation 0.2}

Where \( F_D \) is drag force, \( C_D \) is the drag coefficient, \( \rho \) fluid density, \( A_p \) frontal area and \( v^2 \) is the velocity squared [17,29,38]. This equation explains that drag forces depend on the shape of the body or form drag, density of the fluid or wave drag, and the speed of the swimmer relative to the water. The coefficient of drag is based on the shape and orientation of the swimmer or skin friction [13,14,17,29,38].

Skin friction occurs as the body of the swimmer interacts with the water. A layer of molecules, called a boundary layer forms at the interface of the skin and the water [13,14,17,29,38]. If the swimmer is stationary or moving at a low velocity, the molecules are parallel and smooth. The boundary layer remains because there is little or no friction between the two fluids. As the swimmer’s velocity increases, shear friction forces between the swimmer’s skin surface and the water increase and there is a separation of the boundary layer at the head of the swimmer [43]. As the boundary layer separates, high pressure is created at the head of the swimmer and low pressure at the feet of the swimmer from turbulent flow or eddy resistance [38].

The pressure differential between the head and foot of the swimmer also creates a force perpendicular to the drag force called lift force (Figure 2.1). The equation for lift force is:
\[ F_L = \frac{1}{2} C_L \rho A_p v^2 \]  
Equation 0.3

Where \( F_L \) is lift force, \( C_L \) is the coefficient of lift, \( \rho \) is the fluid density, \( A_p \) is frontal area and \( v \) is the relative velocity of the swimmer.

**Figure 2.1 Lift and drag forces applied to a foil shaped object [38].**

This shows lift and drag forces of a disc. The disc is stationary and the air is flowing around it (the drag arrow pointing to the right). The lift force (arrow pointing upward) is perpendicular to the drag force. Thus the resultant force is in an upward and backward direction. The separation of the airflow around the foil can be noted by the parallel lines that separate around the foil and become more turbulent as it passes the back of the foil. This picture is similar to what happens as a swimmer moves the hand through the water [38].

The drag and lift forces are also affected by the shape of the body in the water. Bernoulli’s principle states there is an inverse relationship between relative velocity and relative pressure in a fluid flow [43]. As relative velocity increases, the relative pressure of the fluid flow around a body decreases. In swimming this explains how a swimmer uses propulsive forces to stay on the surface of the water. As the swimmer increases the relative velocity of the hand in the water, an area of low pressure is created on the dorsal side and high pressure on the palmar side. This increases the resultant lift forces which allow the swimmer to remain on the surface of the water [43] (Figure 2.2).
Figure 2.2  Bernoulli’s Principle- Flow around a foil shape and a hand creates areas of high and low pressure for an upward lift force [38].

Similarities of an air foil and a hand with Bernoulli’s principle. On the left side is a foil shape and on the right side is a hand. They are similar shapes. There is an area of high pressure on the bottom side of the foil and hand. An area of low pressure is above the foil and hand. As velocity increases from the foil to the hand, there is a decrease in the drag force (D) and an increase in lift (L) and the resultant force (RF) [38].

Form drag, or the shape of the swimmers body, influences resistance [17,29,41]. The greater the frontal surface area of the swimmer presented to the flow, the greater the form drag force will be. Swimmers try to minimize turbulent flow by making their bodies as streamlined as possible. Wave drag is the third influence on the swimmer [42]. Since wave drag occurs at the interface of the air and water, it does not affect a completely submerged swimmer. For this reason, swimmers try to maximize the amount of time spent below the surface of the water during a race.

In water, swimming requires lift and drag forces to propel the swimmer in an upward and forward direction. Manufacturers of swimming specific training tools, have developed and marketed dryland swimbenches intended to aid with stroke technique, to take advantage of the water forces (see Figure 2.3). The basic design of the swimbench includes a torso pad and hand paddles connected to a pulley system. Resistance is often provided by varying grades of rubber tubing. To increase resistance or replicate the drag forces, some benches can incline
Biokinetic swimbenches (e.g. Isokinetics, Richmond, CA), used for measuring power, strength, and cardiovascular endurance, have been described in the literature, but presently, are not marketed for swimming coaches use [44-48]. Such swimbenches include a stainless steel cable attached to a recoil system that controls pulling force and the speed, and include a force transducer to measure forces of the swimmer’s hands as they perform the pulling motion [13]. Research using both swimbench designs have shown the pulling motion on the bench is specific enough to increase strength, power, and cardiovascular endurance of a swimmer, but cannot account for the motion of the hand in the medial/lateral direction or body roll which are integral to stroke technique [44-48].

**Figure 2.3 Vasa Trainer Swimbench traditionally used for training swimmers on land**

Vasa Trainer Swimbench (Vasa Inc, Colchester, VT). The swimmer lies prone on the bench and performs the freestyle stroke. Resistance is created by adjusting the incline of the bench and by adjusting rubber tubing that connects with the pulley system. Replication of drag forces occur as the swimmer pulls the body forward against resistance bands (www.vasa.com).
Biomechanics of freestyle stroke
This section describes the biomechanics of freestyle swimming by stroke phase. Details of the stroke provide evidence about the difficulties of replicating actual technique on a dryland devise.

Freestyle is divided into two major phases, propulsive and non-propulsive, defined by where the arm is with respect to the water (Figure 2.4) [45-50]. The propulsive and non-propulsive phases are further broken down into four phases. The propulsive phase is pull/push and the non-propulsive phase is recovery/catch (Figure 2.4). During the propulsive phase, the arm is underwater moving forward to backward and lateral to medial. Lift and drag forces are created as the water moves over the hand and forearm. The motion of the hand and forearm have been studied using underwater three-dimensional cameras to determine the most effective pull through swimming motion [7,13,14,51,52]. The non-propulsive phase occurs when the arm is out of water moving forward, towards the head, in preparation for the next stroke cycle. Since the arm position can be observed from the pool deck, there is less quantified research to support a specific type of recovery, straight or bent arm. Anecdotal information from coaches supports a bent elbow recovery to relax the shoulder [22-24] while decreasing the moment of inertia, allowing for a faster recovery phase.

Although a large amount of variability had been documented in freestyle stroke based on skill levels, preferred distances of the swimmer, gender and age, freestyle is considered a coordinated rhythmic movement [53]. The arms work in opposition, while one arm is under the water in propulsive phase the opposing arm is out of the water in the recovery phase [2,54,55]. Kinematic and electromyographic descriptions of freestyle, in addition to technique differences between elite and novice swimmers are provided below.

Figure 2.4  Four sub-phases of freestyle swimming stroke: catch, pull, push, recovery
The right arm starts at CATCH fully extended in front of the body. As the arm begins to pull water (PULL), it begins to move in a backward, downwards, and lateral to medial direction. The arm passes under the body, parallel to the bottom of the pool, and begins moving in an upward direction, and medial to lateral direction; PUSH. The stroke cycle is completed when the hand breaks the surface of the water and begins moving back toward the head; RECOVERY.

(Catch Phase)

The catch phase is the beginning of the stroke cycle. Catch phase has been shown to range from 23.4-25.2% of the stroke cycle in elite swimmers and up to 28% of the stroke cycle in novice swimmers [18,19,56]. Even though the catch phase is considered non-propulsive, it is a crucial part of the stroke because it helps to anchor the arm to start backwards acceleration.

Catch phase begins when the fingers enter the water. The fingers and hand enter the water just in front of the head, but continue to move forward as the shoulder and elbow are fully extended to allow for the arm and body to glide and rotate away from the pulling arm. Following glide, hand begins moving medial to lateral, backward, and downward.

As the fingertips enter the water, the rotator cuff and scapular musculature act to internally rotate and extend the humerus. The supraspinatus, rhomboids
and upper trapezius muscles fire at a mean average of \( \approx 54\% \) maximal voluntary isometric contraction (MVIC), \( \approx 49\% \) MVIC, and \( \approx 64\% \) MVIC, respectively, in water swimming [30,57]. The anterior and middle deltoid are also active (\( \approx 45-51\% \) MVIC) as the hand enters the water with the elbow slightly flexed and the fingers in a neutral position about 10-20° abducted from the long axis of the head [30,57]. As the swimmer transitions to a lateral body roll, the serratus anterior maintains a constant level of activity (\( \approx 20-40\% \) MVIC) and the pectoralis major (\( \approx 8-17\% \) MVIC) and latissimus dorsi (\( \approx 24-33\% \) MVIC) begin to increase activity to begin the next phase toward pull [30,57-59]. As this occurs the scapula protracts and the elbow moves into flexion, remaining above the wrist and hand [11,12,14,60]. This position increases the humeral thoracic angle, anchoring the humerus into the glenoid fossa to move the body over the arm and frees the wrist and hand to move medial to lateral using a “sculling” motion. Integrated EMG data have shown an increase in biceps brachii and flexor carpi ulnaris activity during this medial to lateral sculling motion [54,61]. Also increases in core muscle activity have been recorded during this phase. The external oblique, rectus abdominis, and gluteal muscles, demonstrate peak activity in the catch phase [62].

Sculling is the act of changing the angle of the hand relative to the water, continuously, as it moves through three directions of motion which increases and decreases the magnitude of the lift and drag forces (Figure 2.5) [17]. The combined effect of the lift and drag forces causes the forward and upward propulsion of the swimmers body. In the beginning of catch phase the angle of attack of the hand is 0° which creates minimal propulsive force, however, the hand increases the angle of attack to about 40° as it moves into the pull phase thus increasing the propulsive forces and forward motion of the swimmer [13].
The lift and drag forces on the hand with respect to the water are the forces that the swimmer uses to propel himself through the water. Top figure shows how the differences in forces created when the angle of the hand in relation to the water does not change and when the angle of the hand changes. As the angle of the hand increases the lift force increases and the resultant force increases, as well, in an upward and forward direction [16,43].

**Pull and Push Phases**

The pull and push phases combine to make up the propulsive phase of the freestyle stroke. Individually, the pull and push phases make up $\approx 20-22\%$ and $\approx 21-25\%$ of the entire stroke cycle, respectively [18,19,56]. The pull phase begins when the hand begins moving backwards, and push phase begins when the hand is directly below the shoulder joint.
The primary muscles acting in this phase are the pectoralis major, latissimus dorsi, triceps, middle trapezius and rectus abdominus [25,30,57,61]. The pectoralis major generates ≈ 70% MVIC and the latissimus dorsi generates ≈ 71% MVIC as the hand begins moving backward in the pull phase. The humeral-thoracal angle decreases as the body begins to rotate back toward the pulling arm. The pectoral major and latissimus dorsi function to adduct, internally rotate, and pull the humerus through approximately 40-65° of horizontal adduction in a downward and caudal direction [25].

As the swimmer transitions from the pull to push phase, the middle and posterior deltoid muscles (≈ 70-76% MVIC) function to horizontally abduct and extend the arm backwards [13,30]. The triceps extends the elbow and the flexor carpi ulnaris radially deviates the wrist to continue a sculling motion [58,59,62,63]. At the end of push phase, the supraspinatus, rhomboids, and upper trapezius muscles increase activity to externally rotate, abduct and elevate the arm out of the water [30,57].

Variation of the underwater pull through have been documented in sprint swimmers of all ages. Skinner [64] noted two primary techniques for pull through following video tape analysis: a bent arm pull through and a straight arm pull through. The figures below depict the two techniques and describe the differences (Figure 2.6a and 2.6b).
The bent arm pull is a variation of underwater pull. The shoulder, elbow and hand are in different directions. This pull through technique favors more body roll back toward the pulling arm (arrow) to generate force from the gluteal and abdominal muscles (www.usaswimming.org).

Straight arm pull through is another variation in the pull through phase. The shoulder, elbow, hand remain in the same direction as the swimmer moves the arm backwards (www.usaswimming.org). This pull through technique uses less body roll and the majority of the force is generated from the shoulder musculature.

The bent arm pull through is similar to the traditional biomechanical analysis of freestyle stroke where hand path follows an “S” shaped pattern; moving laterally and then medially [31]. This type of pull through uses the lift and drag forces of the water created by the sculling motion of the hand and forearm in addition to body roll for forward propulsion. A straight arm pull through results in forward motion from reaction forces with the water. Researchers have proposed that a straight arm pull through utilizes lift forces only [31]. Both pull techniques are described in the literature, and are used by elite level swimmers [13,14,25].
Push phase is the second location where propulsion can be increased prior to the hand exiting the water for recovery. Certain coaching techniques emphasize the swimmer exiting the water when the hand is in line with the hip, while others encourage swimmers to increase their pull through by pushing the hand past the hip before exiting. The later technique was adopted following the 1976 Olympics when a comparison of Olympic swimmers Mark Spitz and Pablo Marallez showed Spitz hand had exited the water when his hand was past his hip. Spitz’s speed was attributed to an increase in lift forces during this later part of the stroke that resulted in a faster swim [14].

Recovery Phase

It is believed that a recovery performed with proper technique helps position the body and arm for an efficient pull and push phase [17,29]. It comprises between 27 and 31% of the stroke cycle depending on the skill level of the swimmer [17,18,29,54]. Recovery is defined from the point the hand exits the water until water re-entry (Figure 2.7).
During the recovery phase, the arm moves towards the head. This illustrates a swimmer using a bent arm recovery (www.googleimages.com).

The primary muscles acting in recovery are the supraspinatus, the subscapularis and the rhomboid muscles. The supraspinatus fires at \( \approx 74\% \) MVIC, the subscapularis at \( \approx 49\% \) MVIC, and the rhomboids at \( \approx 71\% \) MVIC [30] to bring the arm into excessive glenohumeral external rotation and scapular retraction to clear the surface of the water. The elbow and the wrist remain flexed to maximize the end of the pushing phase. During recovery the supraspinatus (\( \approx 79-39\% \) MVIC) and middle deltoid remain active for the entire duration of the phase [30,55,58,59,62]. As the hand exits the water the torso rolls towards the side of the exiting hand and the opposite hand begins the pull phase [62]. At the end of recovery, the shoulder returns to either a neutral or internally rotated position and the hand begins moving forward to begin the next stroke cycle [13].

Two styles of recovery phase arm kinematics have been reported: a straight arm recovery and a high elbow recovery (Figure 2.8) [17]. The difference between the two recovery styles is the timing of the elbow with respect to the hand. Keeping the elbow parallel with the hand has been favored because it is believed to protect the shoulder from injury such as tendonitis or impingement. This high elbow recovery is recommended because it decreases the moment of
inertia which allows for faster rotation of the arm at the start of the next stroke. Also, during a high elbow recovery, the arm remains internally rotated and adducted. This is believed to place less torque on the shoulder joint and set up the arm to enter the water 5-10° abducted from the midline of the body. The internal rotated and adducted position is suggested to prevent injury. At this point during recovery, the elbow is usually flexed, and the hand is about to re-enter the water [30,32].
Figure 2.8  Straight arm recovery is used by both elite and novice swimmers.

This illustrates a straight arm recovery. The swimmer has less elbow flexion compared with the swimmer in Figure 2.7 (www.googleimages.com).

In a straight arm recovery, the shoulder remains externally rotated for a longer period of time. The elbow acts as an anchor and the hand pivots around it. This places the shoulder in a position of impingement which could potentially cause injury. In addition, the wider recovery increases the moment of inertia and creates a longer arc of motion to reposition the hand for water entry. This type of recovery would place a great challenge for the swimmer to position the hand for water entry in an optimal position that would not cause injury. An entry too wide or too close to the midline of the body could place a swimmer at risk for shoulder injury. Elite level swimmers have been noted to use a high elbow, bent arm recovery [17].

Knowledge about stroke kinematics and hydrodynamics help coaches train swimmers to improve performance. Coaches study the characteristics that distinguish elite swimmers: increased SL, coordinated BR, high SR and superposition coordination, and encourage novice swimmers to emulate these stroke characteristics. Drills designed to increase SL or SR are often suggested by
coaches as are dryland training plans specific to swimming [22-24]. Free weights and rubber tubing are commonly used in dryland training programs. Research shows that on land training using weights while performing similar motions to swimming can transfer to improved swimming velocity in the water [65]. In addition motor control research has shown verbal and visual feedback can improve performance [66]. A swimbench, modified to account for body roll, may replicate the specific biomechanics of the stroke in the water. Such a tool would also allow for immediate feedback from a coach about stroke technique to help novice swimmers adopt the stroke characteristics of elite swimmers to swim faster.

The following section discusses differences in stroke techniques documented in elite and novice swimmers, and provides a motor control theory for why these differences exist.

**Section II**

**Elite v Novice Swimmers**

Elite and novice swimmers are distinguished by stroke length (SL), body roll (BR), stroke rate (SR) and coordination modes [2,7,8,15,19,21,31,52,67-70]. During a swimming race the forces from the water on the swimmer change continuously. Increases in a swimmer’s speed result in increases in active drag forces from more turbulent forces. As active drag forces increase, elite swimmers increase SL which decrease resistance from form drag because the body is more streamlined [18,28,37,70-72]. Elite swimmers are believed to make adjustments to stroke rates and coordination as well during swimming competitions that have not been noted in novice swimmers. This section below describes the differences between elite and novice swimmers based on SL, BR, SR and coordination. BR seems to be an important part of SL, so it is included as a subsection of SL.
Stroke Length

Stroke length has been defined two ways in the literature. First, as the distance per cycle the hand travels during a revolution of a freestyle stroke cycle and is calculated using Equation 4:

\[ SL = v \cdot SR^{-1} \quad \text{Equation 0.4} \]

Where \( SL \) is stroke length, \( v \) is the velocity, and \( SR \) is the stroke rate. \( SL \) has also been defined as the displacement of the hip as the hand travels through the water [11,12]. Using either definition, \( SL \) is often measured as the one-dimensional path of the hand moving forward and backwards (cranial-caudal direction) even though it is generally agreed freestyle swimming motion occurs three-dimensionally (Figure 2.9).
Freestyle hand path movement occurs in the three directions of motion. Figure A, the frontal view is motion in the medial-lateral and vertical axis. Figure B, the side view, is motion in the cranial-caudal and vertical axis. Figure C, the bottom view, is motion cranial-caudal and vertical axis. Variations of these hand paths are seen in swimmers of all levels. Different level swimmers are able to adjust these motions to increase velocity [43].

Stroke length has been measured with respect to an external reference point or to the hip in the cranial-caudal axis and is represented in a graph form [12]. Since the angle of the hand with respect to the water affects the active drag forces during propulsion, a straight arm pull might not necessarily produce the fastest swimmer [43]. Faster swimmers are able to use the water in all three directions to increase speed. This makes sense because stroke length has been seen to increase propulsive forces and thus has been suggested as the key to increased velocity [8,70]. Also swimmers of different skill levels have been shown to use varying hand patterns that distinguish their swimming.
A landmark study by Schliehauf [43] in 1979 performed the first three-dimensional biomechanical analysis on tethered freestyle swimming stroke and found three different types of stroke patterns [43]. Differences were noted during the propulsive phase of the stroke. This research indicated elite swimmers used different strategies during the propulsive phase. The path of the hand and the pitch of the hand changed for each swimmer. As a result lift forces, drag forces or an equal combination of both during the propulsive phase were seen for each swimmer [43]. In the first type of stroke pattern (Figure 2.10) the swimmer entered the water using a pressing motion and continued to used a sculling type motion throughout the pull and push phase. This stroke type was shown to maximize the lift forces as the swimmer used a continuous application of force.
Figure 2.10 Hand pattern of Olympic swimmer who maximizes the lift forces during pull through [43].

Figure A. (top) is a side view of an Olympic swimmer. The arrows indicate the motion of the hand from start to finish. The foil shaped objects represent the pitch of the hand as it moves backwards. The resultant force is the center and longest arrow. Arrows show the swimmer moving forward and upward. Figure B (bottom) describes the motion of the hand in the medial-lateral direction. This swimmers hand path is primarily in a medial to lateral direction [43].
In the second type of stroke pattern (Figure 2.11) the swimmer had a deeper catch phase and a straight arm pull through. The swimmer did not use a sculling motion and had a large upward and backward sweeping motion at the finish of the propulsive phase. This swimmer was described as having a fast stroke rate.

**Figure 2.11 Hand path of an Olympics swimmer with large upward movement**

The figure on the left is the side view of the swimmer. The hand follows a steep pitch which results in a forward movement. The figure on the right shows sculling first in a medial direction followed by lateral direction and back medially. This motion created an downward resultant force [43].

In the third type of stroke pattern (Figure 2.12) the swimmer used a sculling motion and had a flatter push phase moving backwards. It was stated that this is a less efficient stroke technique, but suggested the swimmer compensated using strength.
Figure 2.12 Rounded hand path of an Olympic swimmer [43].

The figure on the left shows the side view of the swimmer. The decreased pitch of the hand during the pull phase is represented by a shorter arrow. The majority of this swimmer’s stroke propulsion was generated at the end of the push phase. The figure on the right describes the hand path in the medial-lateral direction. The hand enters the water medially and sculls laterally in the catch phase, the pull is primarily medial and moves more laterally as the hand breaks the surface for recovery. The medial scull creates a large upward resultant force to keep the swimmer in the surface of the water [43].

In 1983, a follow-up study by the same group calculated kinematic and kinetic forces using underwater video [25]. Cameras were placed underwater to view the swimmer from three sides: front, right, left. Landmarks were placed on the index and little finger, hand, metacarpals, shoulder, elbow, clavicular notch and the waist. The dependent variables of hand force and joint torque were determined by first finding the hand angle of pitch, hand sweepback angle, and hand speed. Angle of pitch was defined as the angle between the hand direction and its line of motion. It was determined by taking the inverse tangent of the cross product of four position vectors of the hand (proximal, center and distal). Sweepback angle defined using the angle of the leading edge of the hand or propelling segment [25]. Speed of the hand was calculated by taking the first derivative of the hand position data. Drag and lift forces were then calculated from these variables. The path of the right hand, during the propulsive phase, of elite male swimmers during a freestyle stroke cycle followed diagonal [25] or...
transverse adduction pattern approximately 63° to the body [25,73]. This path of motion was important because it showed that as the angle of the hand changed while it was moving through the water, the propulsive forces changed as well. This suggests that arm path is an important factor when improving performance.

Research focusing on elite swimmers has attempted to define an optimal arm and hand path. Deschodt, Rouard and Monteil [12] measured hip velocity with respect to the wrist, elbow and shoulder trajectories in 44 elite freestyle swimmers [11,12]. Increases in amplitude in the cranial-caudal and up-down directions of the wrist and elbow trajectories had the greatest affect on hip velocity. These findings agree with the second pattern of motion described by Schliehauf's [43] where the hand path was deeper [43]. However, hand paths of the swimmers also had some medial to lateral movements that affected velocity. This pattern of hand movement was also seen in the third pattern of motion described above where the medial-lateral direction and increased motion in the cranial-caudal direction, maximized velocity [16,25]. More recent research suggests a decreased humeral thorax angle during catch, and/or an increased elbow flexion angle during pull through decreases velocity. Novice swimmers tend to display these less efficient patterns. A decreased humeral thoracic angle during catch phase is also referred to as a “dropped elbow”. Following full extension of the arm in the catch phase, the elbow begins moving in the posterior direction followed by the hand. This changes the angle of the forearm relative to the humerus and decreases the amount of usable surface area on the forearm [13]. The elbow flexion should range from between 60-125 ° to use the surface of the humerus, forearm and hand simultaneously during the propulsive phase. When the elbow precedes the hand during the propulsive phase the elbow angle decreases relative to the humerus, so the length of the arm relative to the trunk in the sagittal plane also decreases resulting in less torque generated by the shoulder [25,33]. Higgs and Gallagher [74] used a cable tensiometer and pulley to relate elbow flexion positions to maximum strength during freestyle pull in 30 elite level swimmers. They concluded optimal arm position during the middle of the pull through phase should be wider than the midline with the elbow flexed to
125° of full arm flexion because the greatest amount of force could be generated in this position.

The ability to maintain a long stroke length throughout a swimming race or practice has been identified in elite level swimmers compared with novice swimmers [35,39]. Increased SL results in increased duration during the propulsive phase. Elite male swimmers had mean SL of 2.17±0.2 m during a 100m freestyle sprint. During this race, swimmers increased SL during the final 25 m to increase velocity [8]. Schnitzler et al. [70] compared male and female recreational versus male and female elite swimmers during a 400m freestyle swim. Average stroke length for male elite swimmers was 0.40m greater than recreational male swimmers and 0.08m greater for elite female swimmers than recreational swimmers (elite male 2.54±0.27m, recreational male 2.14±0.26m, elite female 2.15±0.13m, recreational female 2.07±0.15m) [70]. Similar findings were noted for elite swimmers and triathletes during eight consecutive 12.5m swims at varying paces. Swimmers significantly increased SL while triathletes decreased overall SL and increased time in the recovery phase [18].

Comparison of genders swimming at slow, medium and fast velocities demonstrated SR remained constant while SL increased for male swimmers. It is speculated that the larger size of the male swimmers allowed them to generate more power from the shoulder and hand [56]. Interestingly, comparison of international and Olympic level female sprinters demonstrated a decrease in SL in slightly less skilled international swimmers compared with Olympic swimmers [28].

To date, stroke lengths have not been reported on swimbenches for either elite or novice swimmers. Elite swimmers demonstrate greater SL in conjunction with increased BR [21,75]. As noted, until recently, swimbenches lacked a rotational component which may have prevented swimmers from performing their natural SL, thus this variable was not studied on the swimbench. The addition of the rotational component will provide insight about if SL changes occurs during freestyle swimming on a swimbench.
Body roll

Elite swimmers have been shown to display a greater body roll than novice swimmers [33,76,77]. Body roll has been defined in the literature as rotation of the shoulders and hips around the long axis of the body. An effective body roll occurs when the shoulders and hips roll away from the swimmers lead arm, on the long axis, as it is extends in front of the body. This creates a more streamlined body position which decreases form resistance and results in an increased glide duration prior to the start of the catch phase. Another advantage of the body roll is increased strength gained from more efficient engagement of the latissimus dorsi and the pectoralis muscles. When the body turns sideways, there is an increased congruency of the humeral head in the glenoid fossa and the scapula is positioned flush against the thoracic wall which helps to stabilize it while placing the rotator cuff muscles in a position for a more powerful pull. The ability, to coordinate shoulder and hip roll, while extending the arm in front of the body is either not seen in novice swimmers or is seen to a lesser degree than in elite level swimmers [21]. Body roll has been compared between elite and novice swimmers in addition to injured swimmers.

Body roll of between 45-60 º was observed using three dimensional video of elite swimmers for one stroke cycle [7,13,14]. Cappaert et al. [7] defined trunk roll as the displacement of the shoulder roll and hip roll along the long axis. Data in this study looked at only one stroke cycle due to the technology difficulties of data collection under the water [7]. These difficulties are discussed in more detail in the evaluation of swimming section below. Lui, Hay and Andrews [78] measured a mean shoulder rotation of 60.8 º in 10 elite male swimmers. Beekman and Hay [75] compared shoulder roll of injured to non-injured swimmers using three-dimensional analysis and noted injured swimmers to have less body roll during the non-breathing phase of the stroke cycle (49.9 º) and more body roll during the breathing phase of the stroke cycle (57.8 º). Shoulder roll was defined by attaching a plywood fin to the back of the swimmer. The angle between the direction of the vertical fin and the horizontal direction of the posterior shoulders was calculated to determine shoulder roll [75]. Similar
methodology was used to compare body roll and breathing in skilled and unskilled swimmers, however the swimmers were filmed only from the frontal direction using a 2-dimentional camera. Skilled swimmers maintained 46 ° of body roll during breathing and non-breathing trials whereas unskilled swimmers demonstrated large variations in body roll. Variances in body roll were attributed to an inability to coordinate the arm motions to gather enough air to inhale during the breathing phase of the stroke cycle [21]. Yanai and Hay [79]measured both shoulder and hip roll angles during a phase of one stroke cycle in elite male swimmers using a three-dimensional panning periscope system. They noted a coordinated phasic motion in the shoulder and hip, and less hip roll (36°) than shoulder roll (58°). This study further suggested body roll is primarily generated from the reaction of buoyant forces against the body in addition to the path traveled by the hand and the velocity of the arms [33,79]. Unfortunately, these authors did not measure the muscle activity during trunk roll, so it is unknown what amount of muscular activity contributes to body roll. They also used only elite male swimmers, so differences between skill levels and body roll strategies were not discussed.

Decreased or asymmetrical body roll, meaning the shoulders and hip do not move simultaneously through the stroke phase, has been suggested as a pattern in lower level swimmers as well [7,33]. A symmetrical motion of the body increases resistance because the body becomes less streamlined and because the hips roll to catch up with the shoulders increased motion is created. The extra motion causes an increase in resistive drag. Kippenham and Hay [21] reported differences in shoulder and hip roll following a swimming trial. As the importance of body roll becomes more recognized as a means to improve swimmers performance, researchers have created computer models and have even modified swimbenches using high density foams to allow the swimmer freedom to roll the body on the bench [9,76,80].

Computer modeling of swimmers have shown that body roll during swimming increases hand velocities in the medial-lateral and vertical directions [80]. Current data collected on a dryland swimbench modified for trunk roll
measured shoulder and hip roll amplitudes [9]. Their study agrees with the Yanai and Hay [79] in water findings, but with a lesser amplitude of shoulder and hip roll at 31° and 8° respectively [9]. The dryland swimbench study was also able to quantify the coordination of the head, shoulders and torso on the bench during a breathing activity. Differences were noted between genders. The differences between skill levels might also be seen on a bench as they were seen in the water [21]. Some researchers have compared elite and novice swimmers’ body roll, however, these studies looked at only one stroke cycle, just a male population or noted difficulties viewing the full stroke cycle. One study denoted differences in body roll and coordination of the torso suggesting dryland swimbenches may be beneficial for coaching or analyzing body roll in swimmers. Because in the water elite swimmers can coordinate hand paths to optimize propulsive forces and have increased SLs and BRs the need for a swimbench that allows the swimmer reproduce these coordinated motions is necessary. For true evaluation of freestyle swimming, SR needs to be assessed as well. Velocity is related to both SL and SR, thus the speed of the arm motion on the swimbench needs to be reproduced and evaluated as well.

**Stroke Rate**

Stroke rate also plays a role in distinguishing elite swimmers. Stroke rate is defined as the number of stroke cycle completed per minute [52]. There is a direct relationship between a swimmer’s velocity, stroke rate and stroke length as previously described in Equation 4:

\[
\text{v} = \text{SR} \times \text{SL} \quad \text{Equation 0.5}
\]

Where \( \text{v} \) = velocity, \( \text{SR} \) = stroke rate and \( \text{SL} \) = stroke length. For a swimmer to achieve maximal velocity, there needs to be an increase in stroke rate as well as stroke length [13,14]. Swimmers have been shown to maintain velocities or to pace themselves by increasing stroke rate and decreasing stroke length or by decreasing stroke rate and increasing stroke length depending on their racing
strategy [70]. No consensus has been reached regarding whether SR or SL is more important. It has been proposed that the ability to increase or decrease SR and SL is a motor control response from the central nervous system to maintain a high velocity while swimming. In this way, the adjustment of SR and SL changes the coordination of the swimmer throughout the course of a 100m freestyle race [19].

Mostly SR has been examined with respect to the distance of the race, length of the pool and the skill of the swimmer. In general in shorter races, such as a 100m freestyle, elite swimmers used a higher SR compared with novice swimmers [7]. SR and SL cycles were recorded for elite male swimmers during a 100 m freestyle race in a 25 m pool every five meters for each length of a 100 m freestyle. An increase in SR and decrease in SL was reported for the first 50 m of the race, but for the last 25 of the race there was an decrease in SR and an increase in SL [37]. Comparisons between gender show male swimmers have faster SR than female swimmers (46.3± 2.9 and 42.95±1.9 strokes/ min, respectively) for 100 m freestyle [56]. Anthropometrics have been noted to affect SL; increased height is positively correlated with increased SL so SR is not directly compared with SL. Similarly research comparing elite swimmers with triathletes showed no significant differences in SR, but differences in SL [18]. The higher SR in both groups allowed them to swim at an elite level of competition.

Stroke technique could also affect SR. Timing of the acceleration of the hand backwards during the pull phase of the stroke also plays an important role in increasing stroke rate. Elite swimmers who demonstrated an increased linear acceleration during shoulder extension and elbow flexion in the beginning of the pull through phase also had an increased hand velocity which helped to propel the swimmer forward in the water [73]. Deschodt et al. [12] measured elbow and wrist trajectory relative to the shoulder displacement in the anterior-posterior axis in 44 elite level swimmers. They noted that elite swimmers’ elbow position remained in line with the wrist in the anterior-posterior direction relative to the shoulder, suggesting these swimmers accelerated their forearm and hand at a relatively constant speed to propel themselves through the water without
“slipping.” Slipping, as described by Councilman [14], is a common mistake seen in novice swimmers and refers to an increased acceleration of the wrist and forearm during the early part of the pull through phase. As the novice swimmer increases acceleration, the thoraco-humeral angle decreases, shortening the length of the arm, disengaging the latissimus muscles, and preventing the swimmer from using the entire arm as a lever [25]. Another term for this is “spinning the arms” through the water. Stroke rate, like SL, depends on the swimmer’s ability to “feel the water.” This refers to the swimmer developing a sensation of the amount of force against the hand and forearm while pulling through the water. Novice swimmers often have a more difficult time with this, so although the swimmer has an increased stroke rate, they may not have efficiency which will result in slower swimming.

Stroke rates can be easily measured and compared on a swimbench between elite and novice swimmers by counting arm revolutions. To compare the major variables that distinguish elite and novice swimmers, a rotational swimbench could prove to be a valuable tool. If differences in skill level are seen it will support data reported in the water, and will begin to provide ideas about the sensitivity of the sensory motor system between elite and novice swimmers. It is speculated that elite swimmers are better able to maintain stroke technique during competition and practice, because their sensory motor system is more sensitive to feedback it receives from the water while swimming [2,8]. The following section addresses this theoretical construct and ties it back to coordination of freestyle.

**Dynamic systems theory**

It is agreed that stroke technique plays a substantial role in skill level of a swimmer [7]. It appears that faster swimmers are better able to fine tune their freestyle arm stroke during the course of a race compared with slower swimmers [28]. Fine tuning of the freestyle stroke includes maintaining a long stroke length, increasing body roll and stroke rate to achieve a coordinated stroke. From a motor control standpoint, this means the faster swimmers might better control the
degrees of freedom of the arm with respect to changes in the context around them [3,6]. Dynamical systems theory provides possible explanations for how the central nervous system controls volitional movements [3,6].

There have been a number of different theories about control of volitional movement [3,4,26,27,81]. The most popular view was that volitional coordinated motion came from motor programs that were controlled from the cortex only. Each motor program had its own spatial and temporal features and coordinated movement patterns, so when performing a movement, the proper motor program was selected and the task was executed. This idea had shortcomings; first, no explanations were provided for degrees of freedom. It was assumed that each motor program could account for the motions of each individual joint and coordinate it appropriately [6]. This seemed difficult based on the variations of movements at each joint. Second, the motor program was a feed-forward loop, thus no feedback was returned to the CNS to modulate a movement. This suggested that there were motor programs for every movement performed, but no means of correcting a motion. Bernstein’s dynamical systems theory provided a explanation for these problems [6,27]. He proposed that the CNS (both cortex and spinal cord) accounted for coordinated movement through consistent adjustments to the environment in which the movement was being performed.

Dynamical systems theory addressed the two main problems presented by motor programs: degrees of freedom and context-conditioned variability. Degrees of freedom is defined as “the least number of independent coordinates that are needed to identify the positions of the elements of the system without violating any geometric constraints” [6,27]. Degrees of freedom are proposed to be self-organized based on the novelty of a skill. As a novel task is learned, the body first becomes more rigid (decreased decrease of freedom), however as the task becomes more familiar, more flexibility is introduced into the system. This results in a fluid movement where the segments work together and are referred to as coordinative structures [6]. For example, a person just learning to swim freestyle may perform the stroke with stiff arms instead of flexed, relaxed elbows and wrists. They also may use a deliberate arm motion moving first the right and
followed by the left arm, starting each arm motion once the other has finished. The rigid movement of the arms allows the novice swimmer to control the motion. As the swimmer becomes more comfortable in the water, the motion becomes looser or more fluid [6]. The swimmer begins to flex the elbows and the stroke includes a gliding component as the arms start to move cyclically. As the right arm enters the water and glides the left arm exits the water and begins recovery. This pattern is repeated to create forward movement during freestyle stroke. In other words the right and left arm become a single unit also know as a coordinative structure [6,27]. As the swimmer is learning to create coordinative structures, the environment continues to vary [6]. The idea that the swimmer can adjust the stroke based on contextual cues such as the sensation of the water pressure on the forearm is referred to as context conditioned variability and is what makes the sensory motor system dynamic.

Context conditioned variability refers to the notion that with each movement made a novel context is created [6,27]. The following movement made is adjusted based on sensory feedback. Bernstein suggested that degrees of freedom are controlled for by the joints linking together to function as a single unit as anatomical, mechanical and physiological feedback is received during a movement task [6,27]. In swimming the arm moves in a cyclical motion. As it approaches the propulsive phase, the lattisimus dorsi functions anatomically to extend the humerus, while mechanically, it exerts a force on the water. The physiology of this variability refers to the cooperation of the cortex and spinal cord in fine tuning the movements. Application of the dynamical systems changes based on the demands of the task and the challenges that task creates. These are called task constraints. Three types of constraints have been defined: task, environmental and individual [1,6,26,27]. For swimming the task constraint would be the freestyle stroke, and the environmental constraint would be defined as the water, wave form, surface resistance, depth or the pool and the lane lines [2]. Individual constraints refer to the characteristics of the person performing the task i.e anthropometric measures and inherent skill level [2]. Inherent skill levels include muscle fiber type and physiological levels such as how the body utilizes
oxygen as well. Continuous feedback about changes in velocity and spatial awareness come from muscle spindles and proprioceptors and result in corrections or adjustment to movements [6]. These feedback mechanisms are called control parameters and are believed to be responsible for changes in freestyle stroke coordination [2].

Spatial-temporal parameters, such as velocity and timing, serve as cues for swimmers to switch coordinated movement patterns during freestyle swimming [4]. In-phase motions are symmetrical movements of the limbs moving in the same direction synchronously. Out of phase motions are when the limbs move in opposition with each other. Freestyle is an out of phase movement. Laboratory research conducted by Kelso et al. [81] studied coordination of the fingers performing in-phase and out-of-phase movements to determine how coordinated structures respond to various constraints and noted a strong in-phase relationship between limbs. Participants were asked to move right and left index fingers to a target in three conditions: increased velocity, varying distance, and increasing difficulty. For all three conditions participants adjusted movements to reach the targets at the same time suggesting a strong coordination mode between the arms. This research focused on bilateral finger motion and stated that when velocity was increased a spontaneous strong in-phase shift was noted. Others agree with a coordinated shift toward in-phase motion found with increased velocity in wrist flexion and extension movements [3,4,81].

Similar changes in timing between limbs has been noted in running. As velocity increases, stride length increases with concomitant increases in stride rate. Metabolic conservation, mechanical and or energy triggers called parameters have been attributed to these subtle changes in a runners’ stride and rate [27,34]. Likewise, research comparing elite and novice swimmers suggests increases in stroke length and rate as velocity increases [15]. As elite level swimmers accelerate during a sprint swimming race they adopt a coordination mode where both arms are in the propulsive phase for a longer duration of time than when they are in a non-propulsive phase [2,56]. This coordination is seen mostly in the highest levels of swimmers with novice swimmers maintaining a
more even temporal rhythm to their stroke resulting in a more equal amount of
time in propulsive and non-propulsive phases.

Proper freestyle stroke technique consists of a coordinated cyclic motion of
the arms and trunk. There is evidence that increased strength and power, in
addition to high cardiovascular endurance increase a swimmer’s velocity [82].
However researchers agree proper stroke technique is key to fast swimming
[2,12-14,17,32,43,47,52,71,83-85]. Stroke length, stroke rate and body roll have
already been discussed and are major variables contributing to speed [49,86].
The final variable that differentiates elite and novice swimmers is bilateral arm
coordination [2,19,72].

Coordination

Bilateral arm coordination is related to SL and SR [2,19,72]. Elite swimmers
have the ability to change stroke length and stroke rate consistently as they
compete in a race. This might suggest that the elite swimmer may have better
coordination than the novice swimmer [26]. Motor control of tasks requiring
coordination is believed to come from the sensory motor system housed in the
cortex of the brain [6,27]. Freestyle is a complex bilateral cyclic motion that
requires the swimmer to move the arms in opposition through the air and the
water alternately. Motor control theorists speculate that during bilateral
coordinated arm movements, the arms work as a coordinated unit receiving
feedback from the environment [2]. Thus, the more sensitive the cortex is at
interpreting sensory input, the better the coordinated movement becomes. This
phenomenon is believed to be seen in the coordination of elite and novice
swimmers [2]. The following section will explain the tool used to evaluate and
quantify coordination and review the research about coordinative differences in
swimmers.

Coordination of freestyle has been evaluated and quantified using a tool
called the Index of Coordination (IdC) [19]. The IdC is the percentage of lag time
between the start of the propulsive phase of the first arm entry and the second
arm entry. The longer stroke lengths and fast stroke rates seen in elite
swimmers usually result in a shorter duration of time between the start of the propulsive phases between the right and left sides, whereas novice swimmers display a greater duration of time between the start of the propulsive phases. The more time spent in propulsion, the faster the swimmer moves through the water. The IdC is calculated by identifying the following information [19]:

1. Duration of one stroke cycle (s). (Figure 2.13) A stroke cycle is from right arm catch phase till right arm catch phase (t_{sc}).
2. Instantaneous time of the first right arm entry (t_{rpull1}).
3. Instantaneous time of the first left arm exit (t_{lexit1}).
4. Instantaneous time of first left arm entry (t_{lpull1}).
5. Instantaneous time of second right arm exit (t_{rexit2}).

This information is then calculated using the equation:

\[
\text{IdC} (\%) = \frac{(t_{rpull1} - t_{lexit1}) + (t_{lpull1} - t_{rexit2})}{2t_{sc}} \times 100 \quad [19] \\
\text{Equation 0.6}
\]

**Figure 2.13** Representation of one arm cycle to describe coordination during freestyle [19]

![1 Arm Cycle](image)

Water Entry

A: Non Propulsive Underwater Phase: ENTRY and CATCH
B: Propulsive Underwater Phase: PULL
C: Propulsive Underwater Phase: PUSH
D: Non Propulsive Aerian Phase: RECOVERY

Swimmers are then categorized into one of three coordination modes listed below:
Catch-up mode—There is a negative lag time between arms, or the percentage of the stroke cycle the arms are in a non-propulsive phase is greater than in the propulsive phase (IdC<0%). These values have been shown to range from -0.9 ±5.4 to -11.9±4.2 [15] for a 100m freestyle. The right arm is in entry phase while the left arm is in recovery phase. This mode is commonly reported in non-elite swimmers and in elite swimmers in the beginning of a long distance swimming race [19] (Figure 2.14).

Catch up coordination for two stroke cycles of the left arm and one stroke cycle on the right arm.

Figure 2.14 The figure represents two arm phases for a swimmer using a catch up coordination mode (IdC < 0)

There is a greater amount of time with the arms in a non-propulsive phase. The right arm (on top) is in recovery while the left arm (on bottom) is in catch phase. Both of these phase are non-propulsive thus the swimmer is not actively propelling the body through the water using this type of coordination [19].
**Opposition mode** – There is no lag time between arms in this stroke mode because the arms are at extreme opposition ($IdC = 0\%$). This coordination is difficult to achieve and has not actually been reported in the results of the literature, however it is believed that higher level swimmers progress through an opposition mode as they increase velocity. Elite swimmers move through this phase as the sensory-motor system is adjusting itself to move into a superposition mode [19] (Figure 2.15).

**Figure 2.15** The figure represents two arm phase for a swimmers using opposition coordination mode ($IdC = 0$).

During opposition the arm are exactly opposite of each other. The right arm (on bottom) is transitioning from the end of the push phase into recovery (from a propulsive to non-propulsive phase); the left arm (on top) is transitioning from the end of catch phase to the beginning of the pull phase (from a non-propulsive to a propulsive phase). This coordination mode is difficult to achieve, but is believed to be a transition phase between coordination modes for elite swimmers as velocity increases [19] (www.googleimages.com).
**Superposition mode** – There is a positive time lag between arms, or the percentage of time the arms are in propulsive phase is greater than the amount of time in the non-propulsive phase. ($\text{IdC}>0\%$) Elite level swimmers are seen to use this stroke mode in sprint races less than 100 m and have values ranging from $0.3\pm2.0\%$ [15] to $2.53\pm4.4\%$ [19]. The first right arm is in pull phase while the left arm is in the end of the push phase. Both arms are in propulsive phases (Figure 2.16).

**Figure 2.16** The figure represents two arm phase of a swimmer using superposition coordination mode ($\text{IdC} >0$).

The right arm (on top) is in the push phase (propulsive phase) while the left arm (on bottom) is in the beginning of the pull phase (propulsive phase). There is an...
overlap of time where the swimmer is in the propulsive phase. Therefore, the swimmer is spending a greater duration of the stroke cycle in a state of active propulsion. This type of coordination has only been noted for the highest elite swimmers [19] (www.googleimages.com).

Elite and novice swimmers appear to exhibit different modes of coordination based on their SL and SR with elite swimmers better able to transfer between stroke modes [2,8,15,19]. Novices do not show as much variation in coordination modes as elite swimmers often remaining at catch-up or opposition mode, but elite level swimmers are noted to be able to remain at a higher and more effective, superposition coordination mode for a longer period of time [28]. Motor control theorists believe this has to do with the individual swimmers ability to continuously make adjustments to the stroke based on the changing environmental and task demands [26,87].

Swimming coordination can be affected by the constraints of the individual or organism, the task being performed or the environment [18,19,56,71]. For the swimmer, organismic constraints refer to anthropometric characteristics such as arm span or muscle fiber type. These physical traits have been shown to affect velocity between gender [56]. Task constraints refer to the actual task being performed. Freestyle stroke is the task constraint. It requires an out of phase coordinated arm motion to maintain a constant velocity, but some evidence supports movement toward in phase in the most elite level swimmers (super position) [2,56,72]. The environmental constraints propose the greatest challenge in swimming. During a stroke cycle, the arms travel through both air and water. In the water resistance increases two-fold as the swimmer increases velocity. Thus a swimmer with poor stroke technique could have difficulty swimming faster. Other hydrodynamic factors such as drag and resistive forces require the swimmer to make constant adjustment to strokes to maintain speed [39,43]. In elite swimmers, this is where lengthening of the stroke, variations in hand path during pull and push phases, and/or increasing stroke rate occurs. Novice swimmers have not been shown to display these adjustments to the same degree.
Three modes of freestyle stroke coordination pattern have been identified in elite swimmers at varying distances [19]. Chollet et al. [19] quantified coordination in elite level swimmers for the following race distance paces: 50m, 100m, 200m, 400m, 800m, and 1650m. These researchers noted a catch-up coordination for the beginning of each of these events, however for the sprinting events (50 and 100m) swimmers switched coordination modes from opposition to superposition as velocity increased [19]. For the middle distance (200 and 400m) swimmers moved between a catch-up and opposition stroke mode, while distance swimmers (800 and 1650m) used primarily a catch-up stroke mode [19,88]. Potdevin et al. [15] imposed SR tempos on novice and elite swimmers. Both groups were asked to swim at paces of 35, 40, 45, 50, and 55 cycles/min. Swimmers were paced by a beeper placed in their swim caps. As the imposed pace increased to 45 cycles/min, the novice swimmers adopted a superposition coordination mode from a catch-up mode. The same was noted for elite level swimmers, but at a higher pace (50 cycles/min) [15]. The elite swimmers, however, were better able to maintain the superposition coordination than the novice swimmers. Furthermore, the elite swimmers had an increased duration of the push phase to lengthen the stroke, while the novice swimmers shorted their stroke to remain at the higher arm cycling pace [15]. Reasons for switching coordination in both groups were attributed to a switch mechanism known as a control parameter, such as velocity in addition to metabolic cost.

Skill level in swimmers can be distinguished at the highest level of competition. Elite swimmers at the national and Olympic levels demonstrate motor control differences. Hellard et al. [28] measured stroke velocity and technique in national and Olympic level swimmers. They found Olympic swimmers maintained a faster stroke length and stroke rate than national level swimmers. The differences on SL and SR were attributed to a more stable stroke technique coordination pattern in the CNS. In other words, the Olympic swimmers were better able to maintain an efficient stroke coordination pattern for a long period of time while competing [28]. A similar finding was noted for junior national level swimmers ages 15 when swimming for 30 minutes. More skilled
swimmers were able to maintain longer stroke lengths and rates, suggesting a more stable mode of coordination in better skilled swimmers [28]. The subtle stroke technique differences between even the highest levels of swimmers are continually adjusted when a swimmer receives feedback from a coach. This feedback comes from research about stroke technique and ways to decrease the resistive forces placed on the body. Differences between even the fastest swimmers may suggest differences in fine tuning stroke technique from the cortex.

A swimbench modified with a rotational component may better replicate the environmental constraints experienced by swimmers in the water. Based on dynamical systems theory, the elite swimmers should use a superposition coordination on the swimbench and the novice swimmers should display a catch-up or opposition coordination mode. These findings would indicate two important points, first that adding a rotational component provides sensory feedback similar to the water, and second a swimmers' sensory motor system is able to recognize and adapt to this feedback to reproduce stroke technique similar to in the water. Based on this coaches might be able use the swimbench as a means to correct stroke technique and enhance performance.

Section III
Evaluation of Swimming

Coaches are able to provide feedback about swimming technique, as identified in the sections above because extensive research has been done about the resistive and propulsive forces in the pool. In swimming laboratories, various stroke techniques of elite level swimmers are measured directly using in water devises such as the Measuring Active Drag (MAD) system and the velocity perturbations system [29]. Direct measurement of the waters forces is difficult without extensive laboratory equipment, therefore indirect measures have also been developed to determine the forces produced by elite swimmers. Indirect measures include wind tunnels, computer models, underwater 3D video systems, and physiologic measures [17,25,29,39-42,89]. While some of these techniques
are more practical, they still require additional training and are costly. Furthermore, coaches focus on kinematics when providing feedback to swimmers. Presently two-dimensional video taping via digital camera in a water proof casing is most common. The Dartfish system (Fribourg 5, Switzerland) is a 2D video/software program with features such as angle measures and a split screen to allow for more specific feedback to swimmers (www.usaswimming.org). Aside from visual observation, Dartfish might be used by coaches because it provides an underwater view of the swimmers stroke, however most coaches provide feedback from the pool deck because it is most practical. This section describes direct and indirect tools used to evaluate freestyle swimming.

**Direct Measures of Freestyle Swimming**

The two main systems for direct measures of the waters force include the MAD system and velocity perturbation method. The MAD system measures the propulsive force produced by a swimmer while swimming freestyle (Figure 2.17). This device consists of series of pipes attached to grips. Each grip is attached to a force transducer that registers the propulsive force as the swimmer pulls through the water. The data from the MAD system is based on the mean propulsive forces obtained as the swimmer moves. The mean propulsive drag is equal to the mean active drag forces if the swimmer moves at a constant velocity, thus it is assumed that the swimmer is moving at constant velocity. Data collected using the MAD system agree with data collected measuring the passive drag forces of towing a swimmer. However, it was noted that drag forces reported were reduced compared with the estimated drag forces found during active swimming [29,90].
Figure 2.17 The system used to measure active drag during freestyle swimming (MAD system) [29]

This system measures the force of the swimmer while performing the propulsive phase of the freestyle stroke. The data are collected as the hand presses off of the force transducers that are mounted to the bottom of the pool (http://www.ifkb.nl/B4/drag.html).

Another direct measurement of swimming is called the velocity perturbation method. A swimmer performs two swimming trials. The first is the swimmer with no resistance and the second is the swimmer with a hydrodynamic body attached. The hydrodynamic body trails 3.5-4.5 M behind the swimmer so it does not create extra resistance. Equations to calculate force using this method assume the power generated by the swimmer is equal with and without the hydrodynamic body, also kinetic energy is corrected to approximate the active drag forces on the swimmer. The velocity perturbation method can be used with all of the competitive swimming strokes and has been shown to have less error than the MAD system [29,91]. The information gained through both the MAD and velocity perturbation method is useful to quantify active drag forces, but would not be practical for an everyday swimming coach to use with a team.
Indirect Measures

Indirect measures of the forces produced by swimmers have been collected both out of the water and in water, but determined through mathematical calculations. Kinematic information has mostly come from indirect measures. Measuring forces in the water is difficult due to perspective error and water turbulence. These inherent difficulties have resulted in using other means of recreating the forces of the water generated by a swimmer [92]. Mechanical arm models that simulate swimming stroke have been studied in wind tunnels [93,94]. Wind tunnels are used because the air flow follows Bernoulli’s principle. Since the hand creates the shape of a foil, the water traveling quickly over the dorsal surface, like that of the airplane wing, creates low pressure while the water traveling on the palmar surface, travels slower and has a high pressure. While this method provides information about forces, it does not address variations in stroke technique because the mechanical arm is held stationary [94]. This makes it difficult to apply to coaching. Computer models of simulated swimmers have also been created to evaluate the most efficient swimming techniques [80]. However this is not practical for everyday coaching.

Underwater three dimensional video is becoming more commonly used by biomechanists to evaluate freestyle swimming kinematics [8,15,28,39,73,75,76,78,88,90,95,96]. Cameras are set up to view a calibrated space in a pool to record motion in the sagittal and frontal directions. Often a third camera is set up on land to view the top of the swimmer. Data are collected as the swimmer moves through a short distance of swimming. Stroke length, body roll, and stroke rates have been determined using this method of data capture. Stroke length is determined by attaching kinematic markers to the hip and finding the relative displacement of the hip marker with respect to an external reference while the swimmer moves forward [12,35]. This method can only be used in the pool because it includes the glide component of the stroke. Stroke length has also been determined by assessing the placement of the hand into the water throughout the swimming stroke with reference to an external target [12]. Body roll has also been determined using such 3D underwater cameras.
Beekman and Hay [75] utilized a balsa wood fin to describe the amount of shoulder rotation during freestyle swimming. Angular displacement was determined as the change in angle from the starting point to when the fin returned to its original starting point [75]. Payton et al. [77] used a similar method to compare kinematics and breathing strategies in swimmers.

3D video provides useful information about swimming but the data collection process currently requires a skilled biomechanist to hand digitize the data and analyze it. This can be time consuming. For practical purposes, the 3D cameras would not be helpful to provide immediate feedback. Most swim teams now have digital cameras in waterproof casing that can be used for underwater filming. Some software packages such as the Dartfish system are also being marketed to swim teams for performance enhancement and stroke evaluation (www.dartish.com). These software programs are expensive and still require formal instruction to use but are more user friendly than the 3D camera set up. Thus, most coaches still rely on verbal feedback.

Coaches provide feedback based on their observation. However, it is difficult for a coach attempting to correct arm motion during the pull through phase because they can only see half of the stroke phase from the pool deck. Improvement in racing times would suggest some improvement in stroke technique but would not provide the complete picture since the results are potentially also due to increases in strength and power not necessarily biomechanical or technical changes in stroke [45,48,65]. Therefore it is unclear if changes in kinematics are actually changing performance. Video analysis has been shown as a beneficial tool for correction of stroke technique, but presents similar challenges in terms of measuring kinematic changes while the arm is under the water [97].

From the above literature it is also possible a dryland swimming bench could help coaches to provide swimmers with better feedback. This would best be determined if differences in technique can be seen between elite and novice swimmers. The ability to see differences in stroke technique would also provide insight about the motor control and sensory motor system of elite and novice
swimmers. It could provide further evidence that elite swimmers are better able to adjust to changes in their environment better than novice swimmer. If this were true, a dryland tool would help coaches to provide feedback to swimmers.

**Summary of Chapter**

This chapter reviewed the scientific concepts presented in the background (chapter one) of hydrodynamics and freestyle biomechanics. In addition, the distinguishing factors between elite and novice swimmers were highlighted. Stroke length, BR, SR and coordination modes were investigated to highlight variations in freestyle stroke technique between elite and novice swimmers. Dynamical systems theory was presented which proposes differences in elite and novice swimmers arises from the sensitivity of the sensory motor system and the ability to adjust to contextual variation. Finally, an overview of the current tools used to evaluate swimming in the water were presented. These tools can be costly, require extensive training and are not practical for the everyday swim coach. It was concluded that a better tool to evaluate swimmers and provide immediate feedback is needed. Furthermore, if dynamical systems theory holds true, distinguishing stroke characteristics could be seen on the rotational swimbench which would provide a mechanism for coaches to give immediate feedback to swimmers for performance enhancement. At present further research is warranted in this area.
Chapter Three

Methods

Introduction

The purpose of this study is to evaluate the sensory motor system of elite and novice swimmers to determine if freestyle characteristics can be distinguished on a rotational swimbench. This chapter describes the methodologies used during the conduct of the study. Participants are described first and the apparatus used for testing, the rotational swimbench is described second. Testing protocol, data analysis, and dependent variables are then described, with statistical analysis last.

Participants

A sample of 15 elite and 15 novice (elite 8 males, age=24.7±8.0yrs, height=183.8±4.0cm, mass=78.4±7.0 kg; 7 females, age= 26.0±11.0 yrs, height 170.2± 6.0 cm, mass 64.8± 5.6 kg; novice 6 males, age= 41.2±8.5 yrs, height=179.3±8.0 cm, mass= 81.0±1.0 kg; 9 female age=42.0±10.0 yrs, height= 168.3± 7.4 cm, mass=58.5± 25.0 kg) healthy collegiate and masters’ swimmers volunteered for this study. Written informed consent was obtained from each participant prior to implementing the study, which was approved by the university’s human participant institutional review board. Based on reported 100m freestyle times (Appendix A ) [15,18,19,88] participants were stratified as elite if their times were equal to or greater than 75% and novice if equal to or below 74% of FINA national cutoff time [70], respectively.

Participants were included in this study if they reported practicing a minimum of two times each week and previous participation in at least four United States Swimming, National Collegiate Athletic Association or United States Masters Swimming sanctioned meets. Participants were excluded from this study if they reported shoulder pain causing them to alter their swimming training within the past four weeks, or if they had a history of neck, shoulder, or elbow surgery two years prior to the study, or if they were pregnant. Each participant completed a health history questionnaire, which included...
anthropometric and demographic information including starting age of swimming, competition experience, preferred stroke, arm dominance, previous dry land training tool use, and personal best times for 100 m freestyle (Appendix B).

**Apparatus**

Freestyle stroke was performed on a rotational swimming bench (Swim Works, Inc; Santa Rosa, CA) allowing lower extremity kicking and rotation of the trunk (Figure 3.1). The participant was face down on the torso pad with his/her hands in paddles connected to resistive tubing bands initially passing through the pulley at the crossbar approximately 1 m from the torso pad. The participant had the freedom to rotate the body about the cranial-caudal axis, hereafter referred to as the long axis. Strong (Black) elastic tubing (Thera-Band, The Hygenic Corporation, Arkon, OH) provided resistance for the swimming. A force-length curve was determined during pilot testing by calibrating the elastic tubing every six inches [98] (Appendix C). A wooden board with four eye hooks spaced six inches apart was attached to the base of the swimbench (Figure 3.2). Decreasing the length of the elastic tubing increased the resistance at the paddles. This was due to resistance increasing proportionately to the distance the hand was pulling. During pilot testing it was determined that swimmers speed, and skill level, not arm length or height, was the most appropriate factor for setting the resistance level of the elastic tubing.

*Figure 3.1. Picture of the rotational swimbench (Swim Works, Inc; Santa Rosa, CA).*
Frontal view (a) and side view (b). Swimmers, prone on the bench, placed their hands in the paddles which were attached to a pulley system. Paddles attached to a pulley system of strings and the elastic resistance cords. The legs rested on pads attached to the torso pad to allow for kicking.

Figure 3.2. Eyehooks and elastic tubing used to create resistance on the rotational swimbench.
Four eye hooks attached to the wooden board with a piece of elastic tubing 1 m long. To increase resistance, tubing was shortened by placing it on the eye hook closest to the front of the bench in the cranial direction. To decrease resistance, tubing was lengthened by attaching it around the eye hook in the caudal direction. Resistance increased proportional to the distance of the swimmer’s pull length. The shorter the elastic started, the greater the resistance was provided as the pull through occurred. The longer the elastic started the less resistance was provided.

Kinematic data were obtained using eight Eagle and four Hawk digital cameras (Motion Analysis Corp, Santa Rosa, CA) each with a TrueSNAP freeze-frame electronic shutter and a sampling rate of 200Hz. A 1.5 x 2 X 6 m space was calibrated for data collection (Figure 3.3). The swimbench was positioned in
the center of the space. Kinematic data were collected using the EVaRT 5.0 program (Motion Analysis Corp).

**Figure 3.3. Camera set up in the laboratory space**

![Diagram of camera setup](image)

The swimbench was set-up in the rectangular area. Four Hawk cameras were set lower to the ground to capture hand motions. Eight Eagle cameras were positioned in the medial, lateral, and posterior space to capture the arm motions on both sides and trunk rotation during data collection.

**Protocol**

All participants completed a minimum of 30-mins of familiarization with the bench on the day of testing. Once participants felt they could perform a natural stroke, they practiced on the bench at a 100 m freestyle race pace. To eliminate fatigue following the familiarization, participants were given 10-mins of additional rest. Investigators helped participants position themselves comfortably on the torso pad of the bench, secured and stabilized by a foam cushion constructed on each side of the bench (Figure 3.1), and secured the paddles to their hands.
Thirty reflective markers that were used to model the right and left upper extremity and trunk were attached to the participant. Four additional markers were attached to the middle of the front cross bar of the bench, the bottom of the back of the bench, and on the right and left kicking mechanism of the bench (Appendix D). Participants swam freestyle stroke at a warm-up pace for 1-2 mins, and after 2 mins rest, completed four 10 s trials of 25 m at intensities between 70-100% of their 100 m freestyle race pace. Each trial was interrupted for 2-3 s to simulate a flip turn during a 4x 25m event. At this time the participant was instructed to position their body with both arms extended in front of the body and the chin tucked to the chest, until the tester verbally cued them to start the next trial. Once four trials were completed, participants were helped off the bench; all markers were removed; and their skin was cleaned with alcohol to remove adhesive.

Data Analysis

Raw data were smoothed using a low pass Butterworth filter with a cutoff frequency of 4 Hz. Cutoff frequencies were determined via residual analysis [95]. Kinematic data were divided into 3 phases: pull, push and recovery using an interactive algorithm developed in Matlab 7.1 (The Mathworks, Inc, Natick, MA). In absence of the water surface, the origin was set to the C7 marker for the first five frames of the streamlined position before trial 1 (Figure 3.4). This was considered a close representation to the direction of the waters surface.

Figure 3.4. Local 3D Coordinate System
Movements in the cranial or caudal direction were along the x axis, medial or lateral movements were along the y-axis, and upward or downward movements were along the z axis. For cranial-caudal movements, toward the head were positive and toward the rear were negative. For medial-lateral movements, toward the mid-line of the body were positive and away from the mid-line of the body were negative. For the vertical direction, movements above C7 were positive and below C7 were negative.

The phases were defined using position and first derivative data as follows:
Pull: from maximum 3rd MCP marker displacement in the cranial-caudal direction to minimum displacement of the finger in the vertical direction.
Push: from minimum displacement in the vertical direction to the minimum 3rd MCP displacement in the cranial-caudal direction.
Recovery: from end of push to beginning of pull.
Visual confirmation of the beginning of each phase was checked using the model created on the EVaRT program during data collection.
Dependent Variables

Dependant variables were determined for two complete stroke cycles for each of the four trials and divided into the three phases of the stroke.

Phase Durations

- **Duration of pull phase on the swimbench** ($t_{pull}$) – The time (s) from the beginning of pull phase to the time when the 3rd MCP joint is below the shoulder.
- **Duration of the push phase on the swimbench** ($t_{push}$) – The time (s) from the end of pull phase till the 3rd MCP joint crosses the cranial-caudal direction changing from a negative to positive direction in the cranial-caudal direction.
- **Duration of recovery phase on the swimbench** ($t_{rec}$) – The time (s) from the end of pull phase until pull phase begins.
- **Duration of the Propulsive Phase** ($d_{urpp}$) – Sum of the duration of the pull and push phases (s).
- **Duration of the Non-Propulsive Phase** ($d_{urnp}$) – Duration of the recovery phase (s).

Coordinative Structure Dependent Variables

- **Index of Coordination** (IdC) – Mean lag time between the arms with respect to the beginning of the propulsive phase. Presented as the percentage of a total stroke cycle when both arms are or are not in the propulsive phases (%) determined from Equation 6.

$$IdC(\%) = \frac{((t_{pull1} - t_{exit1}) + (t_{pull2} - t_{exit2})) / 2}{t_{sc}} \times 100 \quad [19]$$  

[Equation 6]
Time points at the beginning of arm pull and beginning of recovery were defined as the beginning of the propulsive phases and non-propulsive phase for right and left arms where $t_{\text{pull}1}$ is the time of the first right arm pull, $t_{\text{exit}1}$ is the time of the first left arm exit from the water, $t_{\text{pull}1}$ is the time of the first left arm pull, $t_{\text{exit}2}$ is the time of the second right arm exit from the water, and $t_{\text{sc}}$ is the time of one stroke cycle. The IdC, the lag time between arms, can range from -100 to 100 and has been described for three freestyle stroke coordination modes: catch-up mode ($\text{IdC}<0\%$), opposition mode ($\text{IdC}=0\%$), superposition mode ($\text{IdC} > 0\%$) [19].

Kinematic Dependant Variables

- $E_d^{cc}$ Cranial-Caudal elbow linear displacement on the swimbench (m).
- $E_d^{ud}$ Upward-Downward elbow linear displacement on the swimbench (m).
- $E_d^{ml}$ Medial-Lateral elbow linear displacement on the swimbench (m).
- $H_d^{cc}$ Cranial-Caudal hand linear displacement on the swimbench (m).
- $H_d^{ud}$ Upward-Downward hand linear displacement on the swimbench (m).
- $H_d^{ml}$ Medial-Lateral hand linear displacement on the swimbench (m).
- $H_v^{ml}$ Medial-Lateral hand velocity on the swimbench (m/s).
- $S_s^h$ Stroke symmetry hand ratio of right to left hand displacements in the cranial-caudal, medial-lateral or vertical direction during a stroke cycle (m).
- $S_s^e$ Stroke symmetry elbow ratio of right to left elbow displacement in the cranial-caudal, medial-lateral or vertical direction during a stroke cycle (m).
- BR Body roll angle: The angular displacement of the right posterior shoulder in the medial-lateral and vertical direction about the C7 axis ($^\circ$).

Spatial-Temporal Dependent Variables

- Stroke cycle ($S$) The beginning of right hand pull to the beginning of right hand pull.
• **Stroke length (SL)** The range of hand displacement in the cranial-caudal direction (m).

• **Stroke rate (SR)** number of strokes per minute (c/min).

**Statistical Analysis**

Data were reported as means and standard deviations. All dependant variables were checked to determine if any assumptions were violated. Data were checked for normality using a Shapiro-Wilks test. If normality was violated, a non-parametric Kruskal-Wallis test was used to compare means between variables, and a Friedman’s test was used to compare repeated measures. This was only the case for hand and elbow angular displacement in the medial-lateral direction. Sphericity was checked using Maulchy’s test. If sphericity was violated a Greenhouse-Geisser correction factor was used. The level of significance was set at 0.05.

Separate analyses for left and right were performed on each dependant variable using a two-way mixed model ANOVAs (skill x trial). Symmetry variables were analyzed using two-way mixed model ANOVAs (side x trial). Post hoc analyzes were performed using Bonferroni tests.
Chapter Four

Results

Introduction

The purpose of the present study was to evaluate the sensory motor system of elite and novice swimmers to determine if distinguishing freestyle stroke characteristics, as seen in the water, can be replicated on a rotational swimbench. It was hypothesized if the sensory motor system of elite swimmers was superior to novice swimmers then the following stroke technique differences would be seen on the rotational swimbench: 1) Elite swimmers would change coordination modes from catch-up to superposition during 4 trials of freestyle swimming whereas novice swimmers would remain in catch-up coordination; 2) Elite swimmers would demonstrate greater hand and elbow displacement in the cranial-caudal, medial-lateral and vertical directions than novice swimmers; 3) Elite swimmers would have greater body roll angles than novice swimmers; 4) Elite swimmers would display more symmetrical stroke patterns than novice swimmers; 5) Elite swimmers would display similar SL and SR as reported in historical in water swimming literature.

The results are presented for the index of coordination, kinematics, and spatial-temporal analyses. Since little to no statistically significant findings were seen between elite and novice swimmers on the rotational swimbench, each section begins with a descriptive comparison of stroking characteristics used on the rotational swimbench by both groups. Means and standard deviations are presented as well as graphical representations of both groups kinematics for four trials of freestyle swimming on the rotational swimbench. All selected statistical data is presented in the appendix.

Index of Coordination

Index of coordination values were found to be similar for elite and novice swimmers on a rotational swimbench. The mean IdC for all swimmers was equal
to zero (IdC = 0.07 ±0.07%) indicating catch-up and opposition coordination for all swimmers on the rotational swimbench. This indicates duration of time spent in the non-propulsive phase was longer than the time spent in the propulsive phase per stroke cycle, with similar IdC values for elite and novice swimmers of 0.07±0.07% and 0.06±0.07% (p>0.05). Elite and novice swimmers maintained similar IdC between various trials (lap 1 E = 0.08±0.09%, N = 0.06±0.08%; lap 2 E = 0.07± 0.07%, N = 0.07± 0.09%; lap 3 E= 0.08±0.06%, N = 0.06±0.05%; lap 4 E = 0.06±0.05%, N = 0.06±0.07%) (p >0.05).

Kinematics

Hand Trajectory

Elite and novice swimmers had similar $H_d^{cc}$ on the rotational swimbench for all four of the trials (Figure 4.1). Maximum cranial values with respect to C7 indicate the beginning of the pull phase, and minimum caudal values with respect to C7 indicate the end of the push phase or the beginning of recovery phase. Range of average $H_d^{cc}$ for all swimmers was 0.97±0.12m. Elite swimmers began the pull phase at 0.56±0.08m cranial to C7 and novice swimmers began the pull phase at 0.54±0.06m cranial to C7 (p >0.05). Hand trajectories in the cranial-caudal direction ended -0.55±0.10m caudal to C7 for both elite and novice level swimmers (p>0.05). Elite swimmers right and left hand reached maximum caudal hand position between 30-35 % of the stroke cycle whereas novice swimmers right and left hand reached maximal caudal hand position (end of push phase) between 40-50 % of the stroke cycle. Recovery phase was 57%±0.08 of the stroke cycle for elite swimmers and 55%±0.08 % for novice swimmers hence, no statistically significant findings exists between elite and novice swimmers (p>0.05). This is owing to the large standard deviations within each group and between sides. Overlap of error bars can be seen during the propulsive phase, between 35-50% of the stroke cycle, indicating increased variation in stroke technique as the swimmer transitions from the end of the pull phase to the beginning of recovery phase (Figure 4.1).
Figure 4.1. Hand Displacement Cranial-Caudal Direction. Right and left \( H_{d}^{CC} \) for elite (n=14) and novice (n=14) swimmers average±sd for one stroke cycle for all four trials on the rotational swimbench. Error bars show the similarities in the path of \( H_{d}^{CC} \).

Elite and novice swimmers had similar \( H_{d}^{ml} \) while swimming on the rotational bench for all four trials (Figure 4.2). The medial-lateral values with respect to C7 indicate the swimmers attempt to scull the hand laterally during the pull phase. The minimum values with respect to C7 indicate a medial movement of the hand before the transition from push phase to recovery phase. Lateral hand movement is shown by increasing numbers and medial movement by decreasing numbers. Both elite and novice swimmers started the pull phase of the stroke with the right and left hands approximately 0.44±0.91m lateral of C7. The general pattern followed by both hands moved from lateral to medial, ranging 0.33±0.10m for elite swimmers and 0.32±0.09m for novice swimmers. Maximum lateral hand movement occurred during the first 20% of the stroke cycle for both elite and novice swimmers. Minimum lateral hand displacement
occurred at about 40% of the stroke cycle. During the last 60% of the stroke cycle, the hand moved laterally. No significant differences were found between elite and novice swimmers (p > 0.05). The overlapping lines and standard deviation bars indicate uniformity of hand motion during all phases for both groups and both hands, suggesting motion in the medial-lateral direction was restricted by the rotational swimbench.

**Figure 4.2. Hand Displacement Medial-Lateral Direction.** Right and left $H_d^{ml}$ for elite and novice swimmers for the average of one stroke cycle for all four trials on a rotational swimbench. Elite and novice swimmers demonstrate similar hand paths, moving from lateral to medial to lateral for both right and left hands.

Elite and novice swimmers also demonstrated similar $H_d^{ud}$ for all trials on the rotational swimbench (Figure 4.3). Maximum values occurred at about 20% of the stroke cycle indicating participants initially moved the hand upwards. Minimum values occur at 70% of the stroke cycle indicating the hand is in the middle of the recovery phase. Movement in the negative direction after 20% of the stroke cycle shows the hand moving downward from pull to push phase,
while movement in the positive direction at the end of the stroke cycle indicates
the arm moving from push into recovery phase. Elite and novice swimmers
started their stroke at -0.29±0.03m and -0.36±0.03m below C7, respectively.
Elite swimmers remain at 0.29±0.03m during the first 20% of the stroke cycle,
while novice swimmers raised the hand up approximately 0.10m. Elite swimmers
right and left hand motion moved through a range of 0.44±0.07m and
0.38±0.13m, respectively. Novice swimmers right and left hands motion moved
through ranges of 0.41±0.10m and 0.32±0.12m, respectively. Average of elite
and novice swimmers’ maximum hand placement occurred in the first 10-20% of
the stroke, while average minimum hand placement occurred at 70% into the
stroke cycle in the recovery phase. No significant differences were found (p
>0.05). Overlapping standard deviation bars indicate both elite and novice
swimmers had varying depths of hand pull regardless of their skill level when on
a rotational swimbench.
Elbow Trajectory

A main effect was found for trials in $E_{d}^{ud}$ ($p = .004$) indicating all swimmers had a similar depth of pull (trial 1 = $0.41 \pm 0.10 \text{m}$, trial 2 = $0.42 \pm 0.30 \text{m}$, trial 4 = $0.43 \pm 0.12 \text{m}$), but trial 3 was slightly more shallow, but not significantly ($0.39 \pm 0.12 \text{m}$) ($p = .051$). Elite and novice swimmers were found to have similar elbow displacement in cranial-caudal, medial-lateral directions for all four trials. The path of elbow in the cranial-caudal direction followed a similar bell shaped curve as seen for the hand path, but with smaller amplitudes (elite $E_{d}^{cc} = 0.50 \pm 0.01 \text{m}$, novice $E_{d}^{cc} = 0.49 \pm 0.01 \text{m}$) ($p > 0.05$) (see Figure 4.1). Elite and novice swimmers $E_{d}^{ml}$ followed the lateral, medial, lateral movement pattern seen in hand path, but again with a smaller amplitude of movement (elite $E_{d}^{ml} = 0.18 \pm 0.00 \text{m}$, novice $E_{d}^{ml} = 0.19 \pm 0.01 \text{m}$) ($p > 0.05$) (see Figure 4.2).
**Hand Symmetry**

The majority of right and left hand symmetry values were similar for elite and novice swimmers for all four trials in the cranial-caudal, medial-lateral and upward-downward direction as indicated by symmetry values all close to 1 (Table 4.1). Hand symmetry values were 0.73 for trial 1 in the medial-lateral direction, and 1.4 for trials 1 and 2 in the up-down direction.
Table 4.1 Comparison of Hand Symmetry. This table shows elite and novice right and left hand range of displacement means and standard deviations (m) for cranial-caudal direction (Hd\textsubscript{cc}), medial-lateral direction (Hd\textsubscript{ml}), and up-down direction (Hd\textsubscript{ud}). Hand symmetry ratios (R:L) for elite and novice swimmers for trials 1-4 on the rotational swimbench for the cranial-caudal, medial-lateral and vertical directions are also listed below.

<table>
<thead>
<tr>
<th></th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Trial 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Elite</td>
<td>Novice</td>
<td>Elite</td>
<td>Novice</td>
</tr>
<tr>
<td><strong>Hd\textsubscript{cc} (m)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>1.0±0.15</td>
<td>0.96±0.12</td>
<td>0.94±0.23</td>
<td>0.99±0.13</td>
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<tr>
<td>Left</td>
<td>1.0±0.18</td>
<td>0.92±0.15</td>
<td>0.98±0.19</td>
<td>0.98±0.15</td>
</tr>
<tr>
<td>S\textsubscript{sH\textsubscript{cc}} (R:L)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Hd\textsubscript{ml} (m)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>0.30±0.17</td>
<td>0.27±0.09</td>
<td>0.30±0.10</td>
<td>0.33±0.08</td>
</tr>
<tr>
<td>Left</td>
<td>0.32±0.13</td>
<td>0.37±0.09</td>
<td>0.32±0.11</td>
<td>0.33±0.09</td>
</tr>
<tr>
<td>S\textsubscript{sH\textsubscript{ml}} (R:L)</td>
<td>0.93</td>
<td>0.73</td>
<td>0.93</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Hd\textsubscript{ud} (m)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>0.44±0.16</td>
<td>0.40±0.14</td>
<td>0.41±0.19</td>
<td>0.42±0.17</td>
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<td>Left</td>
<td>0.36±0.12</td>
<td>0.29±0.17</td>
<td>0.39±0.17</td>
<td>0.31±0.15</td>
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<tr>
<td>S\textsubscript{sH\textsubscript{ud}} (R:L)</td>
<td>1.2</td>
<td>1.4</td>
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</tbody>
</table>

Abbreviations: Hd\textsubscript{cc} Hand displacement cranial-caudal direction, Hd\textsubscript{ml} hand displacement medial-lateral direction, Hd\textsubscript{ud} hand displacement up-down direction; S\textsubscript{sH\textsubscript{cc}} hand symmetry cranial-caudal direction; S\textsubscript{sH\textsubscript{ml}} hand symmetry medial-lateral direction; S\textsubscript{sH\textsubscript{ud}} hand symmetry up-down direction
Elbow Symmetry

Comparison of right to left range of elbow motion through the cranial-caudal direction showed that all swimmers moved through a greater distance from cranial to caudal with the left elbow (0.52±0.06m) than with the right elbow (0.49±0.07m) (p= .012). Elbow stroke symmetry in the cranial-caudal direction (SsE_{cc}) for elite swimmers was symmetrical as indicated by values close to 1.0. SsE_{cc} for novice swimmers was slightly less symmetrical with values of trial 1 = 0.97, trial 2 = 0.94, trial 3= 0.96 and trial 4 = 0.94, but not significantly different (p . 0.05). All swimmers demonstrated a similar amount of E_{ml} for the right side (0.19±0.07m) compared with the left side (0.18±0.06m) (p = .072). All swimmers started and ended their stroke with the right and left elbows positioned 0.33±0.07m lateral to C7. Right elbow motion followed a less consistent pattern wavering between medial and lateral motion whereas the left elbow followed a lateral, medial, lateral pattern (see Figure 4.2). SsE_{ml} ranged from 0.74 on trial 1 to 1.2 for trials 2-4 indicating a relatively symmetrical pattern between the right and left elbows. Differences in symmetry were noted for novice swimmers trial 1 (0.74). Novice swimmers range of right elbow displacement was about 20% greater than the range of displacement in the left elbow. Elbow symmetry in the up-down direction was greater for the right elbow than the left elbow for trials 1 and 2. SsE_{ud} values ranged between 1.0 and 1.3 (Table 4.2).
Table 4.2 **Elbow Symmetry.** This table shows elite and novice right and left elbow range of displacement means and standard deviations (m) for cranial-caudal direction (Edcc), medial-lateral direction (Edml), and up-down direction (Edud). Elbow symmetry ratios (R:L) for elite and novice swimmers for trials 1-4 on the rotational swimbench for the cranial-caudal, medial-lateral and vertical directions are also listed below.

<table>
<thead>
<tr>
<th></th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Trial 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ed^cc (m)</strong></td>
<td>Elite</td>
<td>Novice</td>
<td>Elite</td>
<td>Novice</td>
</tr>
<tr>
<td>Right</td>
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<td>0.45±0.07</td>
<td>0.51±0.06</td>
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<td>0.51±0.01</td>
<td>0.49±0.06</td>
</tr>
<tr>
<td>SsE^cc (R:L)</td>
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<td>0.97</td>
<td>1.0</td>
<td>0.94</td>
</tr>
<tr>
<td><strong>Ed^ml (m)</strong></td>
<td>Elite</td>
<td>Novice</td>
<td>Elite</td>
<td>Novice</td>
</tr>
<tr>
<td>Right</td>
<td>0.20±0.07</td>
<td>0.21±0.04</td>
<td>0.18±0.06</td>
<td>0.22±0.08</td>
</tr>
<tr>
<td>Left</td>
<td>0.20±0.05</td>
<td>0.16±0.06</td>
<td>0.18±0.03</td>
<td>0.20±0.09</td>
</tr>
<tr>
<td>SsE^ml</td>
<td>1.0</td>
<td>0.74</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Ed^ud (m)</strong></td>
<td>Elite</td>
<td>Novice</td>
<td>Elite</td>
<td>Novice</td>
</tr>
<tr>
<td>Right</td>
<td>0.47±0.08</td>
<td>0.42±0.11</td>
<td>0.45±0.16</td>
<td>0.43±0.12</td>
</tr>
<tr>
<td>Left</td>
<td>0.43±0.09</td>
<td>0.35±0.11</td>
<td>0.44±0.11</td>
<td>0.34±0.09</td>
</tr>
<tr>
<td>SsE^ud (R:L)</td>
<td>1.1</td>
<td>1.2</td>
<td>1.0</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Abbreviations: Ed^cc Elbow displacement cranial-caudal direction, Ed^ml elbow displacement medial-lateral direction, Ed^ud elbow displacement up-down direction; SsE^cc elbow symmetry cranial-caudal direction; SsE^ml elbow symmetry medial-lateral direction; SsE^ud elbow symmetry up-down direction.
**Medial-Lateral Hand Velocity**

$H_v^{ml}$ was similar for elite and novice swimmers. Both elite and novice swimmers had increased hand velocity in the lateral direction during the first 20% of the stroke cycle, pull phase, with an average maximum velocity of $2.56 \pm 0.60$ m/s. Velocity decreased as the swimmers moved the hand medially during the pull and recovery phases, with the average minimum value of $-2.21 \pm 0.60$ m/s. The greatest variations in $H_v^{ml}$ were seen during the transition from pull phase to push phase indicating a possible attempt to scull the hand to replicate medial-lateral forces performed during in water swimming (Figure 4.4).

**Figure 4.4. Hand Velocity in Medial-Lateral Direction ($H_v^{ml}$).** Average and standard deviations of all swimmers ($n=30$) $H_v^{ml}$ during four trials on the rotational swimbench for a complete stroke cycle starting with the right arm pulling. Large variations of velocities were used as the hand transitioned between pull phase and push phase as indicated by standard deviation bars.
**Body Roll**

BR was similar for elite and novice swimmers. Swimmers started with the right posterior shoulder marker at an angle of $14.3^\circ\pm13.7$ rotated above the direction of C7 and ended with the same shoulder marker at $14.6^\circ\pm16.7$ above the direction of C7. Increasing BR is indicated by increasing values and decreasing BR by decreasing values. The greatest variation in body roll was seen in the first 20% of the stroke cycle and in the last 20% of the stroke cycle as indicated by larger standard deviation bars. In the first 20% of the stroke cycle, the posterior shoulder marker is at its highest peak above the horizontal plane, $32.0^\circ\pm9.0$, and in the last 20% of the stroke cycle, the posterior shoulder marker is at its highest peak above the horizontal plane (-$36.0^\circ\pm2.0$). Maximum BR, occurred at 14-18% of the stroke cycle on right side, the transition from pull to push phase. Minimum BR, -$36.0^\circ\pm2.0$, occurred at 66% of the stroke cycle, during recovery phase (Figure 4.5).

A main effect was found for side in BR ($p = 0.006$) as all swimmers displayed greater range of BR to the right side (right side = $50\pm22^\circ$; left side = $45\pm22^\circ$). Differences between elite and novice swimmers for the right side were not significant ($p = 0.077$) (Lap1: E 53.0±19.0º, N 40.6±17.0º; lap 2: E 53.2±20.0º, N 51.4±29.0º; lap 3: E 56.4±23.1º, N 47.2±29.0º; lap 4: E 55.1±17.0º, N 39.5±21.1º).
**Figure 4.5. Body Roll.** Average and standard deviations of all swimmers BR during four trials on the rotational swimbench for a complete stroke cycle starting with the right arm pulling. Left arm pull began at 44% of the stroke cycle when the right posterior shoulder marker was equal to C7 (0°). Standard deviation bars are greatest in the beginning and end of the stroke cycle.

Spatial-Temporal Characteristics

Elite level swimmers did not demonstrate similar stroke lengths or stroke rates compared with current literature. Freestyle swimming on a rotational swimbench produces a shorter stroke length and a slower stroke rate. Stroke lengths on the rotational swimbench ranged from 1.44-1.01m shorter than stroke lengths in the water (rotational swimbench = 0.9±0.2m, Potdevin et al. [15] = 2.34±0.18m, Nikodelis et al. [88] = 1.91±0.18m, Chollet et al. [19] =2.15±0.2m). Differences in stroke rates were 7.2 c/min less than when swimming on a rotational swimbench than when swimming in the water (Rotational swimbench =
42.7±7.2c/min, Chollet et al. [19] = 49.5±4.3c/min). The propulsive phase (pull + push phase) comprised a shorted duration of the stroke on the rotational swimbench compared with in water data reported in the current literature (Rotational swimbench = 43±0.32% of stroke cycle, Chollet et al. [19] = 48.6±3.5% of stroke cycle, Seifert et al. [56] = 48.8±3.6% of the stroke cycle), while the non-propulsive phase (catch + recovery phase) on the rotational swimbench had a longer duration than non-propulsive phases reported in the current literature (Rotational swimbench = 57±0.08% of stroke cycle, Chollet et al. [19] = 26.2±2.7% of stroke cycle, Seifert et al. [37] = 27.8±3.4% of stroke cycle).

**Summary of Results**

The present study indicates elite and novice swimmers use similar coordination modes on the rotational swimbench when performing 4x10s trials of freestyle swimming. Likewise, both groups hand and elbow displacement ranges were similar. Elite and novice swimmers further displayed similar stroke symmetries, body roll and medial-lateral hand velocities for 4x10s trials of freestyle swimming on the rotational swimbench. Finally, elite swimmers did not demonstrate similar stroke techniques as seen in the water.
Chapter Five

Discussion

Introduction
The present study was the first attempt of using a rotational dryland swimbench to explore sensory motor, kinematic, and spatial-temporal characteristics of elite and novice swimmers. The results indicated that elite and novice swimmers displayed similar stroke characteristics on a rotational dryland bench and these stroke characteristics did not replicate the in water kinematics of swimming, but did slightly replicate in water coordination. This chapter begins by briefly summarizing the purpose and hypothesis of the study. It then explains the implications of the finding and compares them with current research.

Purpose and Hypothesis
The purpose of this study was to evaluate if dynamical systems theory supported any differences in technique of elite and novice swimmers when swimming on a rotational swimbench. This study further examined if kinematic and spatial-temporal differences documented in the literature could be distinguished between elite and novice swimmers on the rotational swimbench. This section discusses the dependent variables measured comparing and contrasting them with current literature on elite and novice level swimmers both on a dryland swimbench and in the water.

Coordination
The primary aim of this research was to distinguish coordination characteristics between elite and novice swimmers on a rotational swimbench. It was hypothesized that elite swimmers would display superposition coordination modes in trials 3 and 4, whereas novice swimmers would remain in catch-up or opposition coordination for all four trials. The data shows elite and novice swimmers do not have distinguishable coordination characteristics on a rotational swimbench. Elite swimmers did not swim using superposition coordination for any of the trials. Both elite and novice swimmers used catch-up/opposition
coordination (E = 0.07±0.07%, N = 0.06±0.07%), as quantified by the index of coordination (IdC), for all four trials. The IdC represents the percentage of time in the stroke cycle when the arms are in either the propulsive or non-propulsive phase [19]. Catch-up coordination indicates that for a portion of the stroke cycle both hands are in the non-propulsive phase; opposition indicates that one hand is in the propulsive phase while the opposite hand is in the non-propulsive phase. This coordination mode has mainly been reported in novice swimmers, but was used by both elite and novice swimmers on the rotational swimbench [19,37,56,41]. Similarities in coordination between elite and novice swimmers may have occurred due to limited effort on the rotational swimbench resulting from the bench’s construct, and/or decreased perception of effort due to reduced sensory feedback. Swimmers in the present study were asked to swim between 70-100% of their 100m freestyle pace as pilot testing revealed 100% effort from elite swimmers placed too much stress on the rotational swimbench. Index of coordination research shows transitions between coordination modes such as opposition to superposition generally occur at approximately 90% of maximum freestyle sprinting speed [18]. As effort was not quantified on the rotational swimbench it is possible that all the swimmers performed at less than 90% of maximum freestyle sprinting speed, so catch-up/opposition coordination should be expected. However it is also possible both elite and novice swimmers swam using similar coordination because they were unable to perceive swimming effort without feedback from the water. This would explain the use of catch-up/opposition coordination for all four trials. Elite swimmers demonstrate increases in stroke length or stroke rates to increase speed during a 100 m freestyle race. These changes in stroke technique are believed to result from sensory-motor input. For example, the sensation of the water on the forearm increases as the swimmers arm velocity increases. On the rotational swimbench, sensory feedback was only felt on the hand, so it is likely that the cortex did not receive adequate feedback to reproduce the type of stroke adjustment seen in the water. As a result, elite and novice swimmers may have
perceived freestyle swimming on a rotational swimbench as a novel task as reflected by catch-up/opposition coordination.

Freestyle swimming is considered a rhythmic motion [53,99]. At a rudimentary level, the arms move in an anti-phasic motion similar to walking or running in the legs [53,99]. Motor control research suggests that these type of rhythmic activities can be performed via central pattern generators (CPG) located in neurons of the spinal cord if initiated by the cortex [34]. CPGs have been shown to control temporal parameters, but do not refine motion without afferent feedback from the cortex [99]. Swimmers were asked to swim at a relatively fast pace on the rotational swimbench, which may have come from a CPG that controlled rhythmic arm motion at a faster pace [34]. However, as elite and novice swimmers demonstrated almost identical stroke patterns on the rotational swimbench, it can be deduced that the feedback from the sensory motor system of elite swimmers was not superior to novice swimmers when the environment of a task was changed. These data suggest the swimming motion can be performed in any environment; however the ability to fine-tune the swimming motion requires more time and practice when the environment is changed.

It is possible the swimbench eliminated the environmental constraints of the water, but still allowed for the cyclic arm motion of freestyle swimming. Environmental constraints in water refer to active drag forces [2]. During a 100 m freestyle sprint race there is an increase in the active drag forces as velocity increases. Also eddy current turbulence, changes in body position and wave drag contribute to fluctuations of drag forces causing changes in the swimming environment [39,40]. Dynamical systems theory suggests elite swimmers accommodate for environmental constraints by increasing SR and SL [2,6] based on the familiarity of the task. These stroke adaptations come from afferent feedback that is sent to the cortex and relayed back through efferent structures that enables the swimmer to create a more streamlined body position, in turn decreasing active drag forces [39,40]. In other words, the sensory motor system of elite swimmers can rapidly adjust to varying contexts and constraints to complete a goal driven task [1-3,6]. For example, Hellard et al. [28] compared
Olympic (elite) and national (less elite) level female freestyle swimmers in a 200 m freestyle and noted Olympic swimmers continued to increase SR in the second 100m of the race whereas national swimmers remain at the same SR the 2nd 100m of the race [28]. The inability of the less elite swimmers to maintain higher SR was attributed to differences in the sensory motor systems of varying levels of elite swimmers. Novice swimmers are reported to decrease SR and SL throughout the duration of a race compared with elite swimmers [7]. Novice swimmers are also described as having a stiffer arm stroke, due to an inability to control and coordinate the various degrees of freedom at the wrist, elbow and shoulder, bilaterally [27]. In a race situation, novice swimmers’ stiffer stroke results in a less streamlined position which increases surface area of the body and active drag. If the environmental restraints were the same on the bench, the characteristics of each skill level would have been seen.

An effort was made to recreate the environmental constraints of the water on the swimbench by providing a rotational component and resistance comparable to the swimmers ability level in the water. This was done in an attempt to determine if sensory motor system differences documented in the water for elite and novice swimmers would prevail on a rotational swimbench. Elite and novice swimmers could not be distinguished on the swimbench which suggests that the sensory motor system of elite swimmers did not adjust more rapidly to swimming on a dryland rotational swimbench compared with novice swimmers. It is also possible that by altering the physical environment we added a dimension of novelty to the task of freestyle swimming, thus the similarities seen between skill levels on the swimbench are invariant characteristics of the cyclic swimming motion which are controlled in the lower centers of the CNS (i.e. CPG) and refined as the cortex receives sensory input [3,6,27] which support these data.

Review of the pre-testing questionnaire revealed only 1 elite male swimmer had ever trained on a swimbench prior to participation. His data did not deviate from the rest of the data, probably because the bench he trained on did not allow for rotation, so freestyle on a rotational swimbench was new for him as
It was hypothesized elite swimmers would demonstrate increased SL and SR, in addition to IdCs greater than zero over the course of the four trials because the sensory motor system would be able to make faster, more spontaneous adjustments compared to the sensory motor system of novice swimmers. These differences were not seen between skill levels. Thirty minutes of familiarization on the rotational swimbench may not have been enough time for elite swimmers to replicate their freestyle stroke technique as they would in the water. Other research using dryland apparatuses to measure swimming kinetics have used repeated sessions of training over four week periods prior to data collection, however they did not compare elite and novice swimmers, nor investigate stroke kinematics [44,48]. Elite swimmers may be superior when adapting to contextual changes in the water, but the transfer from water to land is too great a context change for spontaneous adaptation of the sensory motor system. In other words, although elite swimmers were asked to perform a motion they are familiar with and have practiced many times, placed in a similar position, and provided resistance during the propulsive phase of the stroke, the data support that the sensory motor system perceived freestyle on a rotational swimbench as a novel or unfamiliar task.

Kelso [81] described varying patterns of coordination as leaps from one steady-state to another as a movement task is learned [4,81]. As the CNS becomes comfortable with a movement pattern, it shifts, via feedback from the sensory motor system, to find a more efficient movement pattern. These shifts are continuous and considered transitions through stable states. With each shift the degrees of freedom, originally contained to control a movement, is released and the movement is performed with greater ease [4,81]. Kelso [81] found that participants were able to maintain opposite movement patterns with similar distances between hands when asked to perform a pointing task. He attributed this to coordinative structures reaching a steady-state that is controlled by the CNS [81]. This phenomenon has also been noted in elite and novice volleyball players learning a new serving technique [5]. Three different coordination patterns were recorded for elite and novice volleyball players based on analysis.
of joint coupling in the shoulder, elbow and wrist joints. Their results showed elite and novice volleyball players were not distinguishable by coordination patterns, suggesting that regardless of skill levels, degrees of freedom were altered and adjusted when learning a new task. It is likely the length of training or familiarizing time on the rotational swimbench resulted in both elite and novice swimmers only moving through one steady-state and that the ability to perform the cyclic motion resulted from commands from the lower control centers in the CNS. A longer duration of training time is needed to determine if elite and novice swimmers can be distinguished on the rotational swimbench.

**Kinematic Characteristics**

The second aim of this study was to determine if kinematic differences could be seen between elite and novice swimmers in the cranial-caudal (CC), medial-lateral (ML) and up-down (UD) directions during the propulsive phase of freestyle. It was hypothesized the increased sensitivity of the sensory motor system in elite swimmers would result in longer SL, greater SR, and increased body roll on the rotational swimbench compared to the novice swimmers. Elite and novice swimmers displayed similar freestyle characteristics in the CC, ML, and UD directions for both the hand and elbow. Elite and novice swimmers had an average range of 1.0m of hand displacement in the CC direction and 0.5m of elbow displacement in the CC direction, these are shorter than reported in the current literature [7,12,19,64]. The construction of the rotational swimbench presented a number of mechanical constraints on the swimmer which contributed to lack of differences in elite and novice swimmers on the swimbench and limited displacement values. First the torso pad of the bench was stationary, meaning the torso could rotate around the long axis, but it did not translate in the CC direction. Lack of translation in the CC direction restricted the swimmer to a maximum value dependent on arm length for hand displacement, therefore displacement of the hand and elbow in the CC direction was defined as SL. SL has traditionally been defined as hip displacement during the propulsive phase and are reported to range from 1.19±0.37m to 2.34±0.16m in elite swimmers and from 1.65±0.27 to 2.11±0.15 m in novice swimmers [2,12,28]. This definition
includes the distance the swimmer glides in a streamlined position in the water during the catch phase. Because the bench was stationary, the swimmer did not have a glide phase. To maintain momentum swimmers had to begin the pull phase as soon as the hand returned to the cranial position, effectively decreasing the displacement of the hand and elbow in the CC direction.

Another limitation of the rotational swimbench was the use of elastic tubing to simulate the resistive forces of the water. This required swimmers to overcome the force of the elastic band as it lengthened and to control it as it recoiled during the recovery phase. Controlling the recoil of the band in the cranial direction (during recovery phase) most likely increased the eccentric load on the rotator cuff musculature resulting in a shortening of the arm motion cranially as it tried to control the deceleration of the band. Spigelman et al. [100], found slightly higher infraspinatus activity on the rotational swimbench than reported for in water freestyle by Pink et al. [30] supporting increased resistance during the recovery phase on the rotational swimbench as a possible mechanism for a shorter SL [100]. A shortened arm motion in the recovery phase would account for an earlier start of the pull phase and most likely a decreased length in the push phase as the resistance of the band increased linearly as it increased in length. This meant to maintain a longer SL, the swimmer needed to exert more force at the end of the push phase, while controlling the arm so as to not let it “whip back” to the starting position. In the water, during the recovery phase the arm is relaxed with low levels of muscle activity [30,55]. Hence, increased resistance, as seen on the bench, during the recovery phase is not specific to the demands of in water swimming, and should not be used as a way to evaluate stroke technique.

Medial-lateral displacement of the hand and elbow for elite and novice swimmers was similar as well. As discussed, the resistance mechanism of the bench provided resistance in the CC and UD directions. As a result, resistance in the ML direction came primarily from the arm musculature and gravity, not the elastic band. Previous research on dryland swimbenches has stressed the importance of providing forces in the ML direction to accommodate for the
sculling motion of the hand [17,25,40]. Sculling occurs as the hand moves ML in the water, changing its angle with respect to the direction of the water. The changing angle of the hand causes the water rushing over the dorsal surface of the hand to move faster (low pressure) while the water on the palmar surface of the hand moves slower (high pressure), creating a forward and upward lift force [17,29,39,40]. The data show both elite and novice swimmers attempted to skull the hand in the pull phase of the stroke as indicated by the lateral motion of the hand seen in figure 4.2 and the increases in ML hand velocity in figure 4.4, but were unable to perform this motion to the degree they would in the water. Schleihauf [10] reported on one of the first swimbenches and stated that a mechanism for creating forces in the medial-lateral direction is needed to truly replicate freestyle stroke. The addition of a rotational component and adjusting resistive tubing still did not account for resistive forces in the medial-lateral directions, thus recommendation for modifications of a future design of a rotational swimbench should include a mechanism for replication of the ML forces of the water in addition to a mechanism that allow for a gliding motion in the CC direction.

It was hypothesized that elite swimmers would display more symmetrical, and novice swimmers would display less symmetrical stroke characteristic on the rotational swimbench. The data shows both elite and novice swimmers demonstrated symmetrical stroke patterns. In water data suggests asymmetrical stroke patterns in novice swimmers occur from their inability to maintain coordinated stroke and breathing patterns, whereas elite swimmers demonstrate a more coordinated and symmetrical stroke [8,21]. Since the rotational swimbench is on land, swimmers were not asked to simulate breathing, which could account for both elite and novice swimmers more symmetrical strokes and superposition IdCs. In other words, the rotational swimbench did not allow for replication of the specific freestyle stroke techniques as performed in the water. Using a rotational swimbench, the resistance of the water was not a factor, nor was breathing, so both elite and novice swimmers were able to move the arms through the propulsive phase without constraints of the water. Also, resistance
on the bench was directed from the cranial-caudal and vertical directions which decreased the complexity of the swimming stroke or froze one degree of freedom. Swimmers had only to move the arms through two directions of motion. Data in the water suggest ML movements of the hands are the most variable between swimmers [43]. Three stroke patterns have been described in elite swimmers. Each pattern had a distinctive ML motion of the hand which has been attributed to forward propulsion forces during swimming [43]. On the rotational swimbench swimmers’ hands were placed in paddles attached to a pulley system. The pulleys restrained ML motion which could have externally constrained the degrees of freedom at the glenohumeral joint, in turn influencing the path of the hand and elbow bilaterally. The rotational swimbench may have frozen the degrees of freedom for both elite and novice swimmers resulting in symmetrical arm motion. Since variation of stroke is important in swimmers, the use of a rotational swimbench that constrains the motion responsible for propulsion would not be recommended.

**Body Roll**

Body roll angles (BR) on the rotational swimbench ranged between from a minimum of 39.5° to maximum of 56.4° for all swimmers. Again, no significant differences were found between elite and novice swimmers' body roll. These values represent the total range of body roll for a stroke cycle. A stroke cycle begins with right arm pull and ends with end of the right arm recovery. Maximum values of the data indicate just the right body roll averaged 36.0°. One other study has measured similar amplitudes of body roll on a modified dryland swimbench of 31.0° [9]. In water body roll values range from 45-60° which is larger amount of body roll seen on the swimbench [14, 21, 25, 33, 75, 76, 78, 80, 96].

Differences could also be attributed to differences on definition of body roll and/or measurement techniques. Body roll of between 45-60° was observed using three dimensional video of elite swimmers for one stroke cycle [13] Cappaert et al. [7] defined trunk roll as the displacement of the shoulder roll and hip roll along the long axis and used 3-D under water cameras. Beekman and
Hay [75] defined body roll as the angular displacement of a balsa wood fin attached to a swimmers back and used a 2-dimentional analysis. The current study defined body roll as angular displacement of the posterior shoulder marker relative to the long axis and used 3-dimensional analysis, similar to Cappaert et al. [7]. Comparisons of skill level have not been reported on a rotational dryland swimbench, but have been evaluated in the water for breathing and non-breathing trials. Less skilled swimmers have been shown to roll the body more during breathing strokes than non-breathing stroke cycles [21]. On the swimbench there was limited medial-lateral hand displacement which could have also accounted for smaller body roll angles compared to in water data.

Increased ranges of BR to the right side were found. Swimmers were asked in the questionnaire about breathing side; all but 3 swimmers reported alternate breathing patterns. Thus BR differences cannot be attributed to breathing patterns. Variation in starting and ending positions was seen on the swimbench and in lateral velocity of the hand during the pull phase of the stroke cycle. This could be due to the swimmers attempting to replicate the angle of hand in the water. Current theories about how body roll occurs in the water suggest buoyant forces are a main cause of body roll while other research supports arm motion as a primary force for generating body roll [33,77,78,80,96]. As the body rolls, the swimmer remains more streamlined which reduces the form drag and helps to maintain higher velocities. Yanai and Hay [33] measured BR in water and noted a coordinated phasic motion in the shoulder and hip, with less hip roll (36°) than shoulder roll (58°). This study suggested body roll is primarily generated from the reaction of buoyant forces against the body in addition to the path traveled by the hand and the velocity of the arms. For safety reasons, the swimmers in the current study laid on a torso pad that compressed their torso, so the hip did not display enough freedom to perform separate movements. Interestingly, the swimmers were able to generate BR on the swimbench without buoyant force and with limited medial-lateral motion of the hand. These results suggest BR comes from core musculature in along with other components of coordinated effort of the buoyancy of the water and the path
of the hand. There is limited research about the muscular contribution to BR in the water thus more research may be warranted.

**Spatial-Temporal**

The relationship of velocity, SL and SR has been studied in elite and novice swimmers in the water [7,19]. To date no studies have compared velocity, SL, and SR between elite and novice swimmers on a rotational swimbench. It was hypothesized elite swimmers would demonstrate SL, SR, and ML hand velocities similar to those reported in the literature for in water swimming. The data did not show this. In fact, both SL and SR were decreased as was ML hand velocity. These differences were most likely due to the novelty of the task, lack of specificity in resistive forces and the mechanical constraints of the swimbench on both groups of swimmers, as previously discussed. As such, the comparisons of spatial-temporal characteristics were compared with in water values and between elite and novice swimmers. Results showed decreased SL of approximately 50% for elite and novices (E =0.9±0.2m, N =1.1±0.4m) compared with reported data on both groups for in water sprint swimming (Cappeart et al. [7] E =2.50±0.16m, N = 2.06±0.08; Chollet et al. [19] E = 2.24±0.23, N = 1.32±0.19). Stroke lengths were also slightly shorter in elite swimmers compared with novice swimmers, but SR were higher in elite swimmers compared with novice swimmers which agrees with reported in water data [2,35,36,67,88]. Similarities between elite and novice swimmers on the rotational bench coupled with the shorter SL, decreased SR, and decreased ML hand velocity show the rotational swimbench does not replicate freestyle swimming. Presently, rotational dryland swimbenches do not include resistance mechanism to accommodate for the force and all three directions of motion simultaneously. This limitation results in a lack of sensory feedback to the swimmer decreasing the ability to fine-tune freestyle swimming technique, and would not be recommended to coaches to evaluate stroke technique.
Summary

The results of the current study suggest commonly seen freestyle coordination of elite and novice swimmers can be seen on a dryland rotational swimbench. Kinematics differences such as SR, SL, BR, ML hand velocity can not be distinguished on a rotational dryland swimbench. Based on these findings, the sensory motor system of elite swimmers does not appear to adapt faster, more accurate feedback when swimming on a rotational swim bench compared with novice swimmers. However, the data does provide support for the rhythmic motion of swimming as an invariant characteristic which allowed all swimmers to perform the cyclic motions of swimming even when the physical environment is altered. At this moment the rotational swimbench is not recommended to coaches to evaluate swimmers’ technique as it does not reproduce the environmental constraints of the water needed to provide adequate feedback to the sensory motor system which is necessary to swim in the water. However, the rotational swimbench should not be ruled out as a means of evaluating coordination and gross arm motion in novice swimmers.
Chapter Six

Summary, Conclusions, Recommendations

Summary

It is reported elite and novice levels swimmers displayed different stroke techniques when swimming in the water [7]. Elite swimmers can be distinguished by the ability to coordinate and maintain increased stroke lengths, stroke rates and body rolls compared with novice swimmers. Motor control theorists have suggested elite swimmers have better sensory-motor systems which allow them to fine tune their freestyle stroke during a racing situation whereas novice swimmers are not able to do this.

Coaches strive to help swimmers increase their speed in the water through providing feedback and stroke drills to improve freestyle stroke technique. However, most coaches evaluate stroke technique from the pool deck as it is not practical to coach from in the water. Recently new technologies for evaluating swimming biomechanics have been developed, such as the system for measuring active drag system (MAD) [39], Dartfish, panning perioscopes [33], and underwater 3D kinematic video with analysis software [29], however they are expensive and require extensive training. They do not offer a pragmatic solution for a swim coach who needs to provide immediate feedback to improve the swimmer’s stroke technique to improve speed and to prevent injury. In theory, a dryland swimbench would provide a means to view the pulling phases (which occur underwater) and the recovery phase of a swimmers stroke. This would allow coaches to better assess where in the freestyle stroke cycle the swimmer needs to improve, and provide a means for the swimmer to see if he/she is making appropriate stroke corrections. Previous research supports using a swimbench for strength and power training especially if performed in swimming specific motions [85], but the swimbench has been criticized for not replicating actual hand trajectories as seen in the water [10,101]. Mechanical improvements,
such as a component that allow the swimmer to roll on the long axis have been suggested in the literature [10,16,101]. The purpose of this study was three-fold, first, to determine if the sensory motor system of elite swimmers was superior to novice swimmers when environmental constraints were altered, second to determine if freestyle kinematics could be distinguished between elite and novice swimmers on a rotational swimbench, and third, to evaluate spatial-temporal characteristics of elite and novice swimmers on a rotational swimbench in comparison to in water reported data.

The following hypotheses were proposed: 1) elite and novice swimmers would be distinguished on the rotational swimbench by differences in their Index of Coordination. Elite swimmers would transition into superposition coordination, while novice swimmers would remain in a catch up coordination during four trials of freestyle swimming; 2) elite swimmers would display greater hand and elbow displacement in the cranial-caudal, medial-lateral, and vertical directions than novice swimmers; 3) elite swimmers would have greater body roll angles than novice swimmers; 4) elite swimmers would have a more symmetrical stroke pattern than novice swimmers; 5) elite swimmers would display stroke lengths and stroke rates similar to those reported for in water values from elite swimmers.

Kinematic analyses of 30 collegiate and master level swimmers on the rotational swimbench were performed (Novice n =14; Elite n = 16). Resistance was determined via swimmers speed and adjusted accordingly. Each swimmer performed four 10 second trials on the rotational swimbench. Dependent variables were measured, and included coordination, kinematics and spatial-temporal characteristics. Separate analysis for left and right were performed on each dependant variable using two-way mixed model ANOVAs (skill x trial). Symmetry variables were analyzed using two-way mixed model ANOVAs (side x trial). Post hoc analyzes were performed using Bonferroni tests (p = 0.05).
Results indicated elite and novice swimmers could not be distinguished following four trials of freestyle swimming on a rotational swimbench. The data failed to support all 18 of the hypotheses.

**Conclusion**

The present findings are concluded:

Aim 1. To distinguish coordination characteristics of elite and novice level swimmers on the rotational swimbench.

Hypothesis 1a: Elite level swimmers will transition from a catch-up to super-position freestyle stroke mode during the third and fourth trial of a 100m freestyle on the swimbench. This hypothesis was not confirmed as elite swimmers demonstrated catch-up/opposition coordination for all four trials.

Hypothesis 1b: Novice level swimmers will remain in a catch-up freestyle stroke mode for all four trials of the 100 freestyle on the swimbench. This hypothesis was confirmed as catch-up/opposition coordination was used for all four trials.

Aim 2. To compare upper extremity kinematics between elite and novice level swimmers on a rotational swimbench.

Hypothesis 2a: Elite level swimmers will demonstrate greater displacement of the hand and elbow in the cranial/caudal, medial/lateral, and vertical directions than novice swimmers. This hypothesis was not confirmed as elite and novice swimmers demonstrated similar hand and elbow displacement in the cranial/caudal, medial/lateral, and vertical directions.

Hypothesis 2b: Elite level swimmers will demonstrate greater body roll compared to novice level swimmers. This hypothesis was not confirmed as elite and novice swimmers had similar body roll angles on the rotational swimbench.
Hypothesis 2c. Elite level swimmers will demonstrate a more symmetrical stroke pattern compared to novice level swimmers. This hypothesis was not confirmed, elite and novice swimmers had symmetrical stroke patterns.

Hypothesis 2d: Elite level swimmers will demonstrate medial-lateral hand velocities similar to those reported in the literature. This hypothesis was not confirmed, elite and novice swimmers demonstrated similar medial-lateral hand velocities.

Aim 3. To determine if elite swimmers upper extremity spatial-temporal characteristics on a rotational bench simulate those in water as reported in the literature

Hypothesis 3a: Elite level swimmers will demonstrate stroke lengths similar to those reported in the literature. This hypothesis was not confirmed; elite swimmers had decreased stroke lengths compared with those reported in the literature.

Hypothesis 3b. Elite level swimmers will demonstrate stroke rates similar to those reported in the literature. This hypothesis was not confirmed; elite swimmers had decreased stroke rates compared with those reported in the literature.

Recommendations

The present results indicate that elite and novice swimmers have comparable sensory motor system adaptations when swimming freestyle of a rotational dryland swimbench. All of the swimmers, regardless of skill level, used the same coordination mode and stroke kinematics on the rotational swimbench. Spatial-temporal characteristics were also decreased compared with reported in water data. In the present study, swimmers had 30 mins of familiarization on the rotational swimbench and performed 4x 10 s trials of freestyle swimming. This amount of time was less than previously reported swimbench studies and much less time compared with the amount of time swimmers spend in water training.
Future studies might include a training study to determine if more time is needed on the bench to see differences between sensory motor system of elite and novice swimmers. Increased practice time on the swimbench might reveal differences in sensory motor system for elite and novice swimmers seen as changes in SR and SL.

While kinematic differences in the rotational swimbench between skill levels were not seen, swimmer’s individual in water stroke patterns were also not compared with rotational swimbench data. It would be interesting to collect underwater video of each swimmer’s stroke technique to determine if the rotational swimbench does indeed cater to a particular stroking technique.

Finally the mechanical construct of the rotational swimbench presented a number of limitations, as noted in the discussion. Two main issues were the lack of motion in the torso pad which eliminated the swimmers ability to glide, and the pull of the resistance being in a straight line eliminating resistance in a medial-lateral motion. The latter issue had been reported by previous swimming biomechanists [10,101], and has yet to be resolved. As the sculling motion in the ML direction has been shown to create the forward and upward propulsive forces in the water [43], modifications of the rotational swimbench would be beneficial if the goal of using the bench is for freestyle stroke technique correction. Further kinematic studies are needed to compare the same swimmer on the swimbench and in the water to determine if the recommended modifications do indeed replicate stroke technique.
Appendices

Appendix A

Calibration of Black Theraband Tubing in 6 inch increments

Force – Length curve of heavy resistance Thera-band (The Hygenic Corporation, Akron, OH) tubing over 6 inches of elongation starting at 36 inches and starting at 60 inches. For both starting points forces are curvilinear. Resistance becomes harder at a faster rate as the elastic tubing stretches farther. Setting on the bench was adjusted based on a swimmer's speed as a percentage of the world record. Four settings were created at 6 inch increments: setting 1 was 6” from the crossbar for swimmers whose times were <58 sec; setting 2 was 12” from the crossbar for swimmers whose times were 79-50sec; setting 3 was 18” from the crossbar for swimmers whose times were 71-82 sec; and setting 4 was 24” from the crossbar for swimmers whose times >83 sec.
### Appendix B
Reported Personal Record (PR) 100m Freestyle times and Percentage of FINA National Cutoff Time (WR%)

<table>
<thead>
<tr>
<th>Elite Male (n = 8)</th>
<th>Elite Female (n = 7)</th>
<th>Novice Male (n = 6)</th>
<th>Novice Female (n = 9)</th>
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<td>PR %WR</td>
<td>PR %WR</td>
<td>PR %WR</td>
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<td>0.76</td>
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<td>0.74</td>
<td>0.74</td>
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Appendix C
Kinematic Instrumentation

A total of 30 reflective markers were used to model the right and left upper extremity and torso.

Joint centers

Shoulders: Anterior and Posterior Humerus
Elbow: Medial and Lateral Epicondyle
Wrist: Radial and Ulnar Styloid Processes
Proximal Trunk: C7 and Jugular Notch
Distal Trunk: T8 and Xiphoid Process

Segments

Upper Arm: ½ distance proximal from elbow AC joint
Forearm: ¼ distance proximal from wrist to elbow
Hand: Markers placed on 1st metacarpal joint, 3rd metacarpal-phalangeal joint, and 5th metacarpal
Trunk: Markers placed on the left spinous process of T1 and T6, and the right spinous process of T4 and L1

Appendix D
Demographic information of elite and novice swimmers.
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<td>2</td>
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<tr>
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<td>3</td>
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</table>
Comparison of start age in competitive swimming, dryland training tools used while training, competitive distance swam, preferred stroke, preferred breathing side and dominant hand are listed for elite and novice male and female swimmers. The data are not mutually exclusive as participants could provide more than one answer.
### Appendix E

Commonly reported Dependent Variables in Swimming Research

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<th>Novice</th>
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</tr>
<tr>
<td>40 (cycels/min)</td>
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<td><strong>v(m/s)</strong></td>
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</tr>
<tr>
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<td>1.27±0.12 (40 cycles/min)</td>
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<td>--------------------------</td>
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<td><strong>SL (m/stroke)</strong></td>
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<td><strong>Ratio (SR:SL)</strong></td>
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<td>Propulsive Phase (% of stroke cycle)</td>
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<tr>
<td><strong>Height (cm)</strong></td>
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<tr>
<td>Deschodt, Rouard, Monteil (96,96a)</td>
<td>184.7±0.11</td>
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<td>Lerda &amp; Cardelli (03)</td>
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<td>Seifert et al (05)</td>
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<td>Nikodelis et al (05)</td>
<td>171±0.04</td>
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<tr>
<td>Hellard et al (08)</td>
<td>173±0.06</td>
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<tr>
<td><strong>Arm span (cm)</strong></td>
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<tr>
<td>Seifert et al (05)</td>
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<td><strong>Time 100m(s)</strong></td>
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<tr>
<td>Deschodt, Rouard, Monteil (96,96a)</td>
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<td>Lerda &amp; Cardelli (03)</td>
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<td>Seifert et al (05)</td>
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<tr>
<td><strong>Time 25m(s)</strong></td>
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<tr>
<td>Nikodelis et al (05)(sprint)</td>
<td>13.58±0.08</td>
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<tr>
<td>Nikodelis et al (05)(self pace)</td>
<td>17.15±1.1</td>
</tr>
<tr>
<td><strong>Time 200(s)</strong></td>
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<tr>
<td>Hellard et al (08)</td>
<td>119.48±0.76</td>
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<tr>
<td><strong>Percentage of WR(%)</strong></td>
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<tr>
<td>Seifert et al (05)</td>
<td>90.1±4.2</td>
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<tr>
<td><strong>Breathing Frequency(breath/min)</strong></td>
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<tr>
<td>Seifert et al (05)</td>
<td>33.9±10.2</td>
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<tr>
<td><strong>Stroke Breath(SR/BF ratio)</strong></td>
<td></td>
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<tr>
<td>Seifert et al (05)</td>
<td>1.55±0.64</td>
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<td><strong>Cross Correlation Coefficients</strong></td>
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<tr>
<td>Peak Amplitude (CCFmax (y))</td>
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<tr>
<td>Nikodelis et al (05) (sprint)</td>
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<td>Nikodelis et al (05) (self)</td>
<td>-0.806±0.06</td>
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<td>Time Lag (CCFlag (y))</td>
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<td>Nikodelis et al (05)</td>
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<td>Nikodelis et al (05)</td>
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<td>Peak Amplitude (CCF max(z))</td>
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<td>-0.701±0.14</td>
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<td>0.07±0.1</td>
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**Correlation between Velocity/SR/SL**

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<thead>
<tr>
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<th>Seifert et al (05a)</th>
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<tbody>
<tr>
<td>V/SR</td>
<td>0.56</td>
</tr>
<tr>
<td>V/SL</td>
<td>0.58</td>
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<tr>
<td>SR/SL</td>
<td>-0.34</td>
</tr>
<tr>
<td>V/non-prop</td>
<td>-0.1</td>
</tr>
<tr>
<td>V/push phase</td>
<td>0.2</td>
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<td>V/catch phase</td>
<td>-0.12</td>
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<td>Non-Prop/Prop</td>
<td>-0.83</td>
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### 3D Kinematic Analysis

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<tr>
<td><strong>Hand Pattern Angle (°)</strong></td>
<td>Schleihauf, Gray &amp; DeRose (83)</td>
<td>63.1°±6.8 diagonal to the body</td>
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<tr>
<td><strong>Peak Force Index</strong></td>
<td>Schleihauf, Gray &amp; DeRose (83)</td>
<td>2.37±0.23</td>
</tr>
<tr>
<td><strong>Peak Force Distribution Index (%)</strong></td>
<td>Schleihauf, Gray &amp; DeRose (83)</td>
<td>0.78% ± 0.08</td>
</tr>
<tr>
<td><strong>Scull Index</strong></td>
<td>Schleihauf, Gray &amp; DeRose (83)</td>
<td>1.0±0.19</td>
</tr>
<tr>
<td><strong>Hand Force/unit of time (N)</strong></td>
<td>Schleihauf, Gray &amp; DeRose (83)</td>
<td>48.0±17.7</td>
</tr>
<tr>
<td><strong>Relative Timing of Wrist to Shoulder (s)</strong></td>
<td>Deschodt, Rouard, Monteil (96)</td>
<td>0.51±0.07</td>
</tr>
<tr>
<td><strong>Relative Timing of Elbow to Shoulder (s)</strong></td>
<td>Deschodt, Rouard, Monteil (96)</td>
<td>0.47±0.08</td>
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<tr>
<td><strong>Relative Timing of Wrist to the Elbow (s)</strong></td>
<td>Deschodt, Rouard, Monteil (96)</td>
<td>0.458±0.19</td>
</tr>
<tr>
<td><strong>Hip Velocity (m.s⁻¹)</strong></td>
<td>Deschodt, Rouard, Monteil (96)</td>
<td>2.23±0.51</td>
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<td><strong>Displacement of the Wrist in CC direction (m)</strong></td>
<td>Deschodt, Rouard, Monteil (96)</td>
<td>0.75±0.25</td>
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<td><strong>Displacement of the Elbow in CC direction (m)</strong></td>
<td>Deschodt, Rouard, Monteil (96)</td>
<td>0.96±0.28</td>
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<tr>
<td><strong>Displacement of the Shoulder in CC direction (m)</strong></td>
<td>Deschodt, Rouard, Monteil (96)</td>
<td>1.59±0.39</td>
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<td><strong>Displacement of the Hip in CC direction (m)</strong></td>
<td>Deschodt, Rouard, Monteil (96)</td>
<td>1.79±0.49</td>
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<td><strong>Displacement of the Wrist in ML direction (m)</strong></td>
<td>Deschodt, Rouard, Monteil (96)</td>
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<td><strong>Displacement of the Elbow ML direction (m)</strong></td>
<td>Deschodt, Rouard, Monteil (96)</td>
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</tr>
<tr>
<td><strong>Displacement of the Shoulder ML direction (m)</strong></td>
<td>Deschodt, Rouard, Monteil (96)</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Displacement of the Wrist in V direction (m)</strong></td>
<td>Deschodt, Rouard, Monteil (96)</td>
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<td><strong>Displacement of the Elbow V direction (m)</strong></td>
<td>Deschodt, Rouard, Monteil (96)</td>
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<td>Study</td>
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<td>Deschodt, Rouard, Monteil (96)</td>
<td>0.4</td>
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<tr>
<td>Displacement of the Shoulder V direction (m)</td>
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<tr>
<td>Deschodt, Rouard, Monteil (96)</td>
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### Appendix F

**F-value and P-values for Dependent Variables Main Effects & Interactions**

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<tr>
<th></th>
<th>F-value</th>
<th>P-value</th>
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<tbody>
<tr>
<td>IdC (Trial)</td>
<td>0.137</td>
<td>0.874</td>
</tr>
<tr>
<td>IdC (Trial x Level)</td>
<td>1.166</td>
<td>0.319</td>
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<tr>
<td>IdC (Level)</td>
<td>0.375</td>
<td>0.545</td>
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<tr>
<td>Right H₃ ^CC^ (Trial)</td>
<td>0.568</td>
<td>0.558</td>
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<tr>
<td>Right H₃ ^CC^ (Trial x Level)</td>
<td>2.315</td>
<td>0.113</td>
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<tr>
<td>Right H₃ ^CC^ (Level)</td>
<td>0.176</td>
<td>0.678</td>
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<tr>
<td>Left H₃ ^CC^ (Trial)</td>
<td>0.409</td>
<td>0.588</td>
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<tr>
<td>Left H₃ ^CC^ (Trial x Level)</td>
<td>0.692</td>
<td>0.453</td>
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<tr>
<td>Left H₃ ^CC^ (Level)</td>
<td>0.353</td>
<td>0.557</td>
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<tr>
<td>H₅ ^CC^ (Trial)</td>
<td>0.022</td>
<td>0.338</td>
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<tr>
<td>H₅ ^CC^ (Hand)</td>
<td>0.114</td>
<td>0.738</td>
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<tr>
<td>H₅ ^CC^ (Trial x Hand)</td>
<td>1.313</td>
<td>0.277</td>
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<tr>
<td>Right H₃ ^ML^ - Friedmans</td>
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<td>0.436</td>
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<td>Left H₃ ^ML^ - Friedmans</td>
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<tr>
<td>H₅ ^ML^ - Kruskal-Wallis</td>
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<td>Right H₅ ^ud^ (Trial)</td>
<td>0.335</td>
<td>0.952</td>
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<tr>
<td>Right H₅ ^ud^ (Trial x Level)</td>
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<td>0.536</td>
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<tr>
<td>Right H₅ ^ud^ (Level)</td>
<td>0.509</td>
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<tr>
<td>Left H₅ ^ud^ (Trial)</td>
<td>0.506</td>
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<tr>
<td>Left H₅ ^ud^ (Trial x Level)</td>
<td>0.010</td>
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<td>Left H₅ ^ud^ (Level)</td>
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<td>0.131</td>
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<td>H₅ ^ud^ (Trial x Hand)</td>
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<td>Right E₃ ^CC^ (Trial)</td>
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<tr>
<td><strong>Left $E_d^{CC}$</strong></td>
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<td><strong>$E_s^{CC}$</strong></td>
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<td>(Trial x Hand)</td>
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<td><strong>Right $E_d^{ml}$</strong></td>
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<td><strong>$E_s^{ml}$</strong></td>
<td>(Trial)</td>
<td>0.695</td>
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<td>(Trial x Hand)</td>
<td>0.139</td>
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<tr>
<td><strong>Right $E_d^{ud}$</strong></td>
<td>(Trial)</td>
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<td><strong>$E_s^{ud}$</strong></td>
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<td>(Trial x Hand)</td>
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<td>Right BR</td>
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<td>(Trial x Level)</td>
<td>0.658</td>
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<td>Left BR (Trial)</td>
<td>0.393</td>
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<tr>
<td>(Trial x Level)</td>
<td>0.537</td>
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<tr>
<td>(Level)</td>
<td>2.758</td>
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<td>BR</td>
<td>8.904</td>
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<tr>
<td>(Trial x Side)</td>
<td>0.048</td>
<td>0.828</td>
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</table>
References

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Vita

Tracy Spigelman
March 3, 1974
Philadelphia, Pa

EDUCATION

Temple University, Philadelphia, PA
Graduation: May 2002
Masters of Education – Kinesiology, Athletic Training Emphasis

University of Vermont, Burlington, VT
Graduation: June 1997
Bachelor of Science -- Physical Education
Concentration: Athletic Training

PROFESSIONAL POSITIONS

Aug 2008 -- Present Assistant Professor
Bloomburg University, Bloomsburg, PA

Jan 2008 – May 2008 Clinical Instructor
Eastern Kentucky University, Richmond, KY

Sept 2004 – Dec 2007 GA sponsored by DJ Ortho/ Research Assistant
University of Kentucky, Lexington, KY

Sept 2003 – July 2004 Visiting Instructor Assistant Athletic Trainer
Towson University, Towson, MD

Sept 2002 – July 2003 Clinical Instructor Assistant Athletic Trainer
University of New England, Biddeford, ME

Aug 2000 – May 2002 Head Athletic Trainer/ Guest Lecturer
Clayton High School/Temple University, Philadelphia, PA

Sept 1997 – June 2000 Physical Education and Health Teacher/ Assistant Athletic Trainer
Fulton Elementary School/ JP McCaskey High School, Lancaster, PA

SCHOLARSHIP
Publications
1. Peer Reviewed

121

2. Non-peer reviewed journals

Spigelman, TH. Identifying and Assessing Glenohumeral Internal-Rotation Deficit; *Athletic Therapy Today, May/June 2006*

3. Book Chapters


4. Manuscripts in review


5. Abstracts


Spigelman, T.H. Glenohumeral Range of Motion on Pre-Pubescent Swimmers Over a Twelve –Week Season. *National Athletic Trainers Association Annual Meeting*, June 2003

**PRESENTATION**

1. International


2. National
Spigelman, T.H. Glenohumeral Range of Motion on Pre-Pubescent Swimmers Over a Twelve –Week Season. *National Athletic Trainers Association Annual Meeting*, June 2003

3. Regional/State


Spigelman, TH, Swanik, KA, Hamstra, KL, Swanik CB. Differences in Glenohumeral Range of Motion in Pre-Pubescent Swimmers Compared to Controls Over a Twelve Week Season. *Eastern Athletic Trainers Association Annual Meeting*, January 2004

4. Oral

Swimming Biomechanics and Common Injury Presentation, University of Kentucky *Wildcat Symposium*, May 2007

Spigelman, T.H. Glenohumeral Range of Motion on Pre-Pubescent Swimmers Over a Twelve –Week Season. *National Athletic Trainers Association Annual Meeting*, June 2003

5. Poster

Spigelman, TH, Swanik, KA, Hamstra, KL, Swanik CB. Differences in Glenohumeral Range of Motion in Pre-Pubescent Swimmers Compared to Controls Over a Twelve Week Season. Eastern Athletic Trainers Association Annual Meeting, January 2004

STUDENT PROJECTS
Wonnell, AC, Spigelman, TH, Uhl, TL, Mullineaux, DR: Electromyographic analysis of core musculature during freestyle swimming on a rotational swimbench

Hill, C, Spigelman, TH, Uhl, TL, Mattacola, CG, Shapiro, R: Dry-land Freestyle Swimming: Comparison of a Traditional and Two Multi-Planar swim benches

ORGANIZATION AND CERTIFICATIONS

Certifications

Kentucky Athletic Training Licensure, Feb 2008

Accredited Clinical Instructor, Easter Kentucky University, May 2006

Accredited Clinical Instructor, Towson University, September 2003

Accredited Clinical Instructor, University of New England, October 2002

Athletic Trainer, certified, National Athletic Training Association (#049802515; Date April 1998- present)

Adult CPR, certified, American Red Cross, 1988-present

Memberships

American Society of Biomechanics, 2008 - present

National Athletic Trainers’ Association, 1997 – present

Kentucky Athletic Trainers’ Society, 2005 -- present


HONORS

United States Masters Swimming Research Grant Jan 2009 $3000

USA Swimming Science and Technology Grant Jan 2006 – March 2008 $15,000

University of Kentucky Commonwealth Research Scholarship Oct 2007 $1000

KATS scholarship Jan 2005 $500

Northern Athletic Conferences Academic Honor Roll, University of Vermont, 1996-1997

Women’s Leadership Program, University of Vermont, 1996

Dean’s List, University of Vermont, 1993, 1996, 1997

PROFESSIONAL DEVELOPMENT

Symposiums & Conventions
Mid-Atlantic American Conference on Sports Medicine, Harrisburg, PA Oct 2008
North American Conference on Biomechanics, Ann Arbor, MI Aug 2008
8th Annual Congress of Physiotherapists, Istanbul Turkey Oct 2007
Lexington Clinic Shoulder Symposium, June 2005 Lexington, KY
National Athletic Trainers Association Annual Meeting & Symposium, Atlanta, GA June 2006
National Athletic Trainers Association Annual Meeting & Symposium, Indianapolis, IN, June 2005
National Athletic Trainers Association Annual Meeting & Symposium Baltimore, MD, June 2004
National Athletic Trainers Association Annual Meeting & Symposium, St. Louis, MO, June 2003
National Athletic Trainers Association Annual Meeting & Symposium, Dallas, TX, June 2002
Pennsylvania Athletic Trainers Society State Meeting & Symposium, Harrisburg, PA June 2002
National Athletic Trainers Association Annual Meeting & Symposium, Los Angeles, CA June 2001
Pennsylvania Athletic Trainers Society State Meeting & Symposium, Harrisburg, PA June 2000,
Annual Primary Care Sports Medicine Symposium, Hershey, PA, 2000
Pennsylvania Athletic Trainers Society State Meeting & Symposium, Harrisburg, PA June 1999
West Chester University Sports Medicine Continuing Education Conference, West Chester, PA, 1999