A KINEMATIC ANALYSIS OF THE “BREAK-OUT” PHASE OF THE FREESTYLE, BACKSTROKE, AND BUTTERFLY SWIMMING STROKES

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAI`I AT MĀNOA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

KINESIOLOGY

AUGUST 2014

By

Stephen B. Allnutt

Thesis Committee:

Jan Prins, Chairperson
Nathan Murata
Charles Morgan

Acknowledgements

A sincere thank you to Dr. Prins for his guidance and support throughout this project and my tenure at UH. None of this would have been possible if not for the opportunities he has given me to work in the Aquatic Research Lab and learn about swimming research over the past seven years.

I would also like to acknowledge Dr. Murata and Dr. Morgan for their generous time and effort to help me improve my writing and critical thinking skills. Without them I would not have the background in research and reviewing literature.

I'm very thankful to Dr. Donnon was critical to the success of this study, providing his services to help with the statistical analysis, and providing clarity into our results.

Additionally I'd like to thank Coach Victor Wales and all of the UH swimmers who participated in the study. Their performance and expertise was invaluable.

Finally I'd like to thank all of the other students who helped with data collection in the Aquatic Research Lab: Amarens Genee, Carley Miller, Shelby Montgomery, Samantha Restivo, Ilia Reyes, and Daniel Worden. They were a pleasure to work with and made this process much smoother.

Abstract

This study examined the effect of different time intervals between when a swimmer begins their initial stroke until their head breaks the surface on three variables: horizontal hip velocity when their pull begins, velocity when their head breaks the surface, and peak velocity during the first stroke. Twelve university (Division 1) swimmers performed their breakout-stroke and were analyzed using motion analysis software. Paired-samples *t*-tests were used to compare self-selected breakout time, elongated breakout time, and shortened breakout time. The mean breakout time was 0.40 ± 0.22 (n=5) for Freestyle, 0.82±0.11 (n=5) for Backstroke, and 0.25±0.17 (n=3) for Butterfly during normal breakout trials. When all strokes were combined, significant differences were found in head break velocity during self-selected trials (1.60±0.20 m/s) when compared to elongated (1.43±0.22 m/s, $p \leq 0.01$), and shortened (1.39±0.19 m/s, $p \leq 0.01$). Regression analysis showed a significant positive correlation between head break velocity and maximal velocity during the first pull.

Table of Contents

List of Tables

List of Figures

<u>Figure</u> **<u>Page</u>**

List of Abbreviations

Abbreviation	**Definition**
HB	The moment the head breaks the plane of the surface**.**
PB	The moment the first pulling motion begins
BOT	The time differential between PB and HB
HBV	The instantaneous horizontal hip velocity in m/s at HB
PBV	The instantaneous horizontal hip velocity in m/s at PB
FPV	The maximal instantaneous horizontal hip velocity during the first stroke

Chapter 1. Introduction

As with all athletic events that require racing over set distances, the goal of competitive swimming is to complete the event in the shortest possible duration. In swimming, the race can be divided into four phases, each of which has to be completed within each length of the pool. These phases are (1) The push-off; (2) A series of underwater kicks that immediately follow the push-off; (3) Surface swimming; (4) and the Turn or "Finish" of the race. It is critical to maintain momentum by decreasing drag forces and increasing propulsive forces during each of these phases, including the time taken between transitions in order to achieve a minimal time to complete the race distance. The transition between phase 2 and 3, which is the time taken to complete the series of underwater kicks followed by a single arm stroke , the intent of which is to propel the swimmer to the surface is termed the "Breakout."

To our knowledge, this is the first time a kinematic analysis of the swimming breakout has been attempted. Therefore, the purpose of this study was twofold. (1) Define the timing of the major kinematic variables that create a breakout that minimizes reductions in speed; and (2) identify the major timing elements of the breakout stroke for Freestyle, Backstroke, and Butterfly.

Statement of the Problem

The purpose of this study was to examine the effect of three different timing variables on the breakout stroke for Freestyle, Backstroke, and Butterfly. More specifically the study seeks:

a. To define the breakout stroke for The Freestyle (Front Crawl), Backstroke, and Butterfly strokes

b. To examine the relationship between incorrect timing and the reduction of hip velocity when the head breaks the surface.

c. To compare the differences between the hip velocity profiles of the breakout stroke during Freestyle, Backstroke, and Butterfly swimming.

Need for the Study

Up to this time, there have been no formal studies that clearly defined the breakout stroke, and the associated kinematic parameters, and a subsequent discussion relating to the importance of correct timing of the breakout stroke as it contributes to overall swimming race outcomes.

Operational Definitions

Independent Variables Measured:

- Breakout Time (BOT): The time between the beginning of the pull, and when the head breaks the plane of the surface.

Dependent Variable(s) Measured:

- Maximal Hip Velocity during First Pull (FPV): Defined as the maximal value for the velocity of the hip during the first stroke in the horizontal direction.
- Hip Velocity at Pull Begin (PBV): The instantaneous longitudinal velocity of the greater trochanter at the initial movement of the arms during the “downsweep.”

- Hip Velocity at Head Break (HBV): The instantaneous longitudinal velocity of the greater trochanter at the moment when the head breaks the plane of the surface.

Delimitations

1. The study participants were 12 healthy swimmers between the ages of 18 and 21 years old. The subjects were all members of the University of Hawaii Varsity swim team, which ensured compatible levels of swimming experience.
2. Measuring the hip velocity directly helps eliminate confounding factors of calculations that involve center of mass calculation.

Limitations

1. The results of this study are limited to the subject population studied and the equipment used.
2. The subjects were asked to make modifications to their normal swimming technique.
3. Using a repeated-measures design introduces the possibility that the swimmers modified their technique based on the previous trial.

Chapter 2. Literature Review

Literature Review Overview

The “breakout” stroke is an important transition between two phases of swimming races, the underwater kicking phase and the stroke phase. Consequently, improving the breakout stroke could improve competitive swimming times. The breakout stroke for Freestyle, Backstroke, and Butterfly are all complex full-body motions, performed near maximal effort during a race. Many of the factors that are required to create a successful breakout stroke have not been studied. In large part, what an optimal breakout stroke consists of varies by discipline, and is undefined in the literature. Furthermore, the majority of the current research has focused on the Freestyle stroke, with limited research conducted on the Backstroke or Butterfly strokes. Due to the lack of overall research directly related to the breakout, this review of literature will focus on the phases of the swimming race prior to the breakout stroke: the push-off, glide, and underwater kicking phases. Inferences will be made as to how the literature on these phases is related to the breakout stroke.

There are many different perspectives from which to view and analyze swimming efficiency. Honda, Keys, Lyttle, Alderson, and Bennamoun (2012) make an argument that no one method of measurement currently available will show the full picture of what constitutes swimming. With this rationale, the studies examined for the review of literature will cover a select range of topics using a variety of measurement techniques.

Resistive and Propulsive the Forces in Swimming

Forward motion in swimming is created when the forces produced by the arms and legs to propel it forward exceed the intrinsic forces of the water that resist motion. Honda et al. (2012) suggests that there are three ways to increase swimming velocity: (1) to increase total propulsive forces; (2) to decrease total resistive forces; and (3) a combination of both. Toussaint and Truijens (2005) added that when the hands or feet travel backwards to apply force, some water is directed in unnecessary directions and when minimized will also contribute to improvement of mechanical efficiency.

Resistive Forces Encountered in Swimming

There are three types of resistive forces, or drag forces, that a swimmer faces while moving forward in the water: form drag, viscous or skin friction drag, and wave drag (Rushall, Sprigings, Holt, & Cappaert, 1994; Toussaint & Truijens, 2005). Form drag, also known as frontal resistance, is related to the shape of the body and its position relative to the direction of travel. Changes in form drag may play a role in how effective the breakout stroke is. Skin friction drag is a factor of the roughness of the swimmer's body and swim suit. Rushall et al, (1994) explained how "skin roughness, body contouring, hair, and swim suit fabrics are examples of the roughness that creates friction as a swimmer moves through water"; causing a minor effect upon performance with increased velocity . Skin friction drag is not assumed to play a significant role in the difference between breakout stroke styles. Wave drag is only encountered by swimmers when they are at or near the surface (Vennell, Pease, & Wilson, 2006; Toussaint & Truijens, 2005). There is minimalized wave drag at depths .75m beneath the surface and deeper (Vennell et al., 2005). Swimmers will be encountering wave drag for the first time during the length of the pool during the breakout stroke, it is hypothesized that wave drag will play a large role in how different styles of breakout strokes are performed. Both Vennell et al. (2005) and Novias et al. (2012) claim that wave drag makes up 50-60% of the total drag when at the surface.

Propulsive Forces in Swimming

The initial propulsive force during a swimming race comes from the swimmer pushing off the starting block or the wall in a jumping fashion, after this they must use different strategies to provide propulsion. Rushall et al. (1994) states "… drag and lift forces have to be considered as contributing to the propulsion of swimmers". The hand and forearm act at a hydrofoil to produce these two forces (Toussaint & Truijens, 2005). Depending on the angle of attack of the hand and arm, drag and lift forces will vary. Each stroke is different in this regard, though only in breaststroke is lift though to play a significant role. Drag forces in the backward direction caused by the hands and the feet are the primary sources of propulsion during the underwater dolphin kicking and stroke phases.

Hip Velocity as the Primary Focus

Hip velocity in the horizontal direction is commonly used to measure temporal changes that occur within stroke cycles (Takeda, Ichikawa, Takagi, & Tsubakimoto, 2009, Takagi 2004). One stroke cycle is classified as the time between consecutive right hand entries into the water. All four competitive swimming strokes have periods of alternating acceleration and deceleration within each cycle that are caused by imbalances in propulsive and resistive forces (Tella et al., 2007, Barbosa et al., 2006 & Barbosa et al., 2005),. Large fluctuations in velocity of the swimmer result in greater energy expenditure due to the need to overcome drag forces and inertia (Nigg, 1983)

Previous methods used by (Craig, Termin, & Pendergast, 2006) to track changes in velocity during swimming have used a belt around the swimmer's waist connected by a fine line to a direct current generator positioned on the pool deck. Using synchronized video recording and digital recordings of the DC generator's output they were able to evaluate how velocity changed over time during swimming movements. In swimming reflective markers cannot be adopted due to the dissipation and refraction of light in the underwater environment. However, makers are essential if the software used for data analysis has an "automatic digitizing feature, the use of which can dramatically reduce inaccuracies and the time taken to identify the pertinent joint segments.

More recent methods have used 2d video analysis without the attached line, allowing for less restriction of the swimmer and less equipment. Consequently, motion analysis programs such as Vicon Motus allow for a valid method of collecting and analyzing multi two-dimensional video (Kiran, Carlson, Medrano, & Smith, 2010).

To compensate for this, Ceseracciu et al. (2011) has used a method of swimming motion analysis without the use of markers.

A study by Psycharakis (2007) showed that the hip velocity as tracked by six JVC KY32 CCD cameras does not accurately reflect center of mass (CM) motion on the X or horizontal axis. Calculations of CM on land are based on how gravity acts on the different limb segments. Many of the calculations used in modern biomechanics are based off an article by Dempster (1955) that details joint axis and limb center of gravity. These calculations do not take into account different fat distribution patterns in different people that would change how much downward force is applied to each limb segment. For this reason, using land-based CM calculations is likely a flawed way to analyze swimming. In addition, it can be argued that "center of mass" is a function of gravity, and consequently are minimized in the water. We have chosen to use a more straight forward measurement that is longitudinal displacement as a function of elapsed time (velocity in the longitudinal plane of motion)

Context and Definition of the Breakout Stroke

Sweetenham and Atkinson (2003) briefly touch on the breakout stroke in their book *Championship Swim Training*:

> "The sprint swimmer needs to attain top speed in the first two strokes when sprinting. On racing-start practice, the swimmer should get to the stroke rate from the breakout stroke to develop this skill. The swimmer must focus all concentration on the breakout stroke because the ability to reach top speed can determine success or failure" (p. 109).

Maglischo (2003) describes a proper Freestyle breakout in his book *Swimming Fastest*:

> "In Freestyle events, they should begin to flutter kick just before they start that first stroke. This will establish a rhythm so that they come through the surface swimming the front crawl stroke" (p. 273).
>
> "The first arm stroke should begin when swimmers near the surface and the head should break through the surface as the first arm stroke is being

> completed… This pull should bring the body upward through the surface traveling forward at race speed" (p. 273)

These passages give a brief glimpse into the breakout stroke, and highlight the importance of beginning the surface swimming phase with the maximal velocity. There is no evidence in the literature that the kinematics of the first stroke are any different for the breakout stroke than they are for other strokes taken during surface swimming. Maglischo (2003) defines the portions of the underwater pull in Freestyle, Backstroke, and Butterfly to be the "downsweep", "insweep", and "upsweep." These terms can be applied to breakout strokes as well. Using this framework, the major events that can be clearly marked based on two-dimensional video analysis are (1) beginning of the downsweep (pull begin, [PB]), and (2) the head breaking the plane of the surface (head break, [HB]). The instantaneous horizontal velocity of the hip during head break will be measured as a variable signifying how quickly the body is moving at the stroke phase begins.

After pushing off the wall or diving in, a swimmer's velocity will inevitably diminish as drag forces act on their bodies (Takeda et al., 2009). In order to minimize the reduction of speed caused by drag forces acting on their bodies, after the push-off, the majority of competitive swimmers in Freestyle, Backstroke, and Butterfly events stay beneath the surface in a hydrodynamically streamlined position with their arms outstretched overhead, choosing to provide propulsion with only their legs (Lyttle, Blanksby, Elliot, & Lloyd, 1998).

Underwater dolphin kick (UDK) is the most common style of kick performed during the underwater portion of the length for the strokes Freestyle, Backstroke, and

Butterfly. This underwater portion must be completed and the head must break the surface at maximum of 15 m off the wall, from which the swimmer is pushing off (FINA rules 5.3, 6.3, 8.5 CITE) after which they must begin to swim on the surface. Optimizations of the push-off and underwater kicking phases have been studied (Lyttle et al., 1998, Atkinson, Dickey, Dragunas, & Nolte, 2013) Changes that results in a decrease in drag are advantageous to achieving a faster time. The timing of the stroke that takes place during the transitions between the underwater phase and surface swimming has not been previously studied. Shimadzu, Shibata, and Ohgi (2008) found that while mid-pool swimming is a large factor in race outcomes, the turn, start, and underwater kicking phases are also important.

Takeda et al. (2009) described a transition phase from the beginning of the underwater dolphin kick until the breakout stroke is initiated with the “downsweep”. This study showed that swimmers must minimize the deceleration from the initial dive or push-off phase through the stroke phase and that ultimately initial speed did not make more than a small difference in speed during the stroke phase. This finding provides reason to study the breakout stroke. If initial speed during the dive or push-off affects speed during the underwater kicking phase but does not affect speed during the stroke phase, it is possible that the timing elements of the breakout may be a factor. The transition between the underwater kicking phase and the stroke phase varies depending on the stroke. In Freestyle and Backstroke a pull with one arm is initiated while the swimmer is submerged under the surface, and their head will break through the surface during this stroke. In Butterfly a double-arm pull is initiated in a similar fashion. The breakout stroke is the beginning the stroke phase of the race.

Overview of the Phases Before and After the Breakout

Due to the lack of previous research into the timing elements of the breakout stroke, this study has chosen to examine three specific events that occur during the breakout stroke: the beginning of the pull, the moment the head breaks the plane of the surface, and peak horizontal hip velocity within the first arm-stroke. We will define the breakout time as the elapsed time between the pull begin and the head break.

The Push-off, Glide Phase, and Underwater Kicking Phases

The purpose for analyzing the push-off phase, glide phase, and underwater dolphin kicking phase is that these phases will potentially affect the breakout stroke by determining how much inertia the swimmer has when the breakout stroke begins. Speed in one phase has been shown to have an effect on speed in the next phase. Takeda et al. (2009) showed that initial speed from the dive or push-off affects speed during the glide and underwater kicking phases. A high velocity at the beginning of the glide phase caused the underwater kicking to be performed at a higher velocity. The researchers found minimal correlation between speed during the initial speed and speed during the stroke phase. It is not yet known if speed during the underwater kicking phase plays a role in speed during the stroke phase, or how the timing of the initial stroke affects speed during the stroke phase.

Optimal depth underwater for the glide has been studied in multiple ways. Lyttle et al. (1998) used a towing system connected to force transducers that towed swimmers at varying depths and velocities measuring the drag created. They found that for velocities 1.9 m/s and 2.2 m/s there was less drag force when the midline of the body was submerged to a depth of .4m and below. Novais et al. (2012) used Computational Fluid Dynamics modelling (CFD) to perform a similar study and found that depths below .75m were ideal for minimizing drag during the glide phase. For both of these studies, swimmers were put into what the authors described as an ideal streamlining position with the torso elongated, arms above the head and legs together. If swimmers were to streamline in a less efficient way then this would affect their velocity and in turn the optimal depth.

Lyttle, et al (2009) found that the optimal velocity at which to begin underwater kicking is 1.9 m/s to 2.2 m/s. Due to the inability to breathe and race rules, swimmers can only afford to spend a limited amount of time underwater kicking. Ignoring physiological demands the optimal amount of time underwater would be equivalent to the amount of time they can travel at a speed that is faster than they can swim on the surface (Craig et al., 2006). They must also be careful to only spend time performing the underwater kicks if it allows them to maintain a higher velocity when compared to swimming on the surface. Takeda et al. (2009) noted that if swimmers decelerate below the speeds achieved during surface swimming, they must accelerate once they reach the surface which would take large amounts of energy while reaching lower swimming velocities. Swimmers that are more effective at propelling themselves using the UDK will benefit from performing UDK for a longer distance, effectively delaying the breakout stroke. While von Loebbecke, Fish, Mark, and Mittal (2009) emphasized that there is no single kinematic parameter that will define efficiency in the dolphin kick, Atkinson, Dickey, Dragunas, & Nolte (2013) found that greater symmetry in the sagittal plane of the UDK is correlated with kicking at a greater velocity. It is likely that for elite dolphin kickers who can maintain a speed near or above 1.5 m/s that the depth should be kept below .75 meters for the majority of their kicking, choosing only to travel in shallower water when preparing for the breakout. For all these stated reasons, swimmers need to weigh the benefits of underwater dolphin kicking vs. the cost of restricted breathing for their chosen race stroke and distance. Achieving and maintaining a higher velocity prior to the breakout stroke will give the swimmer more inertia with which to perform the breakout stroke.

The Stroke Mechanics Associated with the Breakout

We will refer to the initial armstroke as the “breakout stroke”. Due to the lack of previous research into the timing elements of the breakout stroke, in this study we have chosen to examine the instantaneous horizontal hip velocity during three specific events that occur during the breakout stroke: the beginning of the pull (PB), the moment the head breaks the plane of the surface (HB), and peak horizontal hip velocity within the first pull (FP). Each variable had a time component and a velocity component. The breakout stroke begins when the swimmer begins the first pull while submerged, and concludes when the swimmer’s head has broken the place of the surface. These three instantaneous hip velocities are our dependent variables. We titled the elapsed time between PB and HB the breakout time (BOT), this is our independent variable. We chose to select these three moments to measure the hip velocity because we believe that the timing between these elements determines the success of the breakout stroke. Our most crucial dependent variable is the speed with which the head breaks the surface (HBV) to begin the next phase of the race. A higher HBV velocity is assumed to be beneficial to the overall swimming time.

The Stroke Phase

The most important phase of the race to total race outcome is the surface swimming, or stroke phase. Also termed “mid-pool swimming”, it is the time the body has surfaced and commenced the propulsive arm strokes on the surface. This phase consists of synchronized arm and leg movements at the surface. In the context of the “breakout” this is the conclusion of the motion, constitutes the “Stroke Phase”. The factors associated with the swimmers progress on the surface encompass a wide range of variables. It is likely that performing the breakout in a more optimal manner will allow the swimmer to perform the stroke phase faster.

Chapter 3. Methods

Subjects

Twelve members of a Division I swim team participated as subjects for the study. Nine were male and three were female, ranging in age from 18 to 21. All video and data were collected during the course of a single intercollegiate swimming season, between the months of October 2011 and October 2012. The UH Manoa Institutional Review Board approved this study on human subjects. Written informed consent was obtained prior to data collection.

Filming & Data Collection

Two high-speed Basler A602 digital cameras were used for data collection, complete with Computar 5mm fixed focal length lenses. Film speed was set to100 frames per second. The camera was placed in custom underwater housing (The Sexton Company, Salem, OR). The camera was orientated perpendicular to the direction of travel. Calibration was performed using a 1m x 1m rectangular calibration frame set up along the path of the swimmers a distance of 5.4 meters from the camera. The camera was placed at a distance of 7.8 meters away from the push-off wall to capture the execution of the breakout in its entirety. This required that the swimmer’s hip needed to be visible to the camera prior to the first pulling motion. In addition to the camera used for data collection, two other cameras were used to capture a frontal view and a lateral view of the push-off.

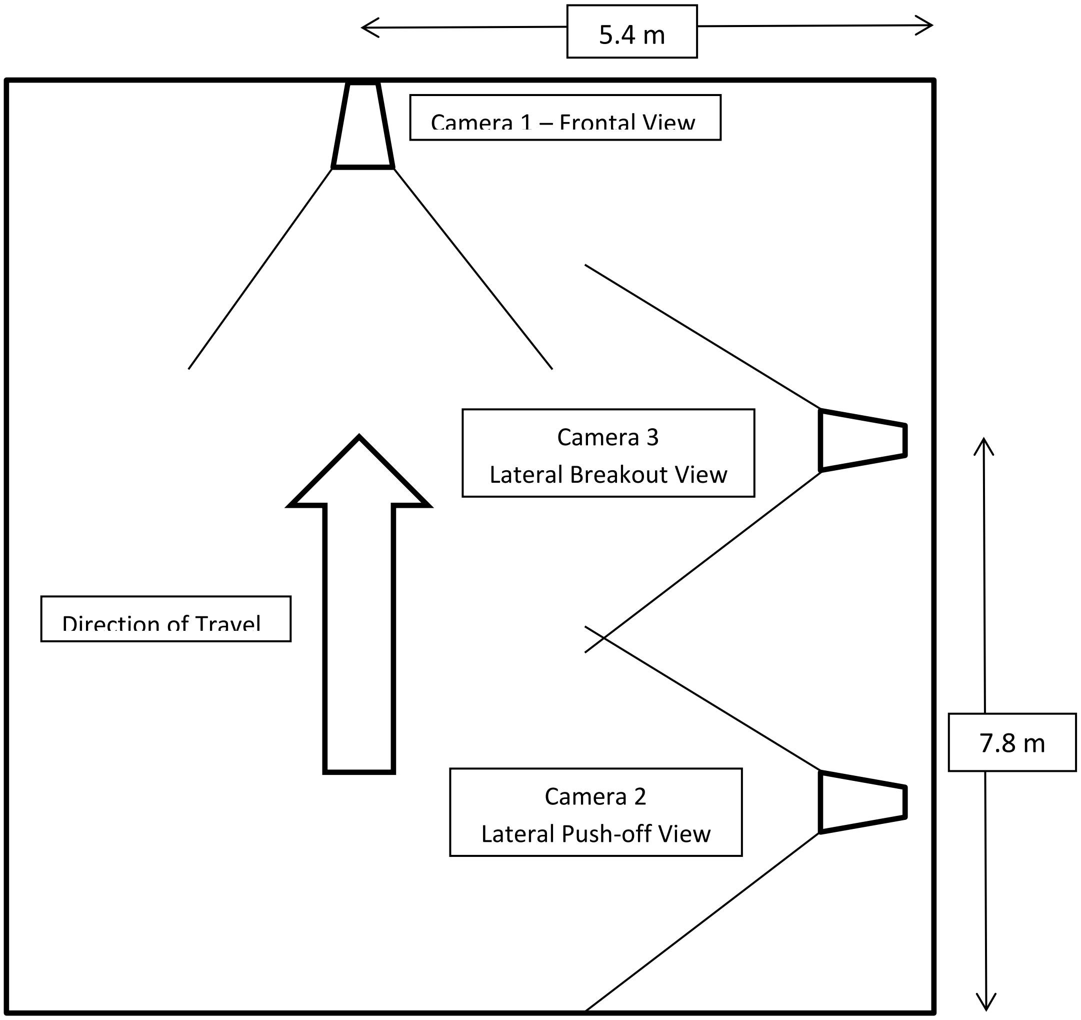

Figure 1: Diagram of filming configuration

Marker System

The process of software digitizing necessitates the identification of joint segments that are pertinent to the motion being analyzed. To allow for this process, custom-designed strands of waterproof 'light emitting diodes" (LED) markers, powered by a portable battery pack, were placed along the complete length of one side of the subject's body These lights were placed the right side for Freestyle and Butterfly, the left side for Backstroke (Table 1). The markers were located so as to be visible to the lateral camera (Fig. 1)

Joint Marker	**Description of Marker Placement** (relative to anatomical position)
Finger Tip	Medial side of 5th phalange
Wrist	Medial side of wrist joint
Elbow	Lateral to the olecranon process
Shoulder	Estimation of the gleno-humeral joint when performing full shoulder flexion
Hip	Lateral portion of the greater trochanter
Knee	Lateral approximation – center of the axis of the knee
Ankle	Lateral portion of the lateral malleolus
Toe	Superior lateral portion of the distal 5th metatarsal.

Table 1: Marker Placement

Figure 2: LED Marker System

Experimental Procedures

Swimmers were videoed while performing their specialty stroke. Eleven swimmers performed one single stroke (Butterfly, Backstroke, or Freestyle), and one swimmer performed both Butterfly and the Freestyle. Each subject performed 3 trials, each trial consisting of (1) the push-off; (2) the underwater kicks; and (3) the breakout stroke, performed at maximal speed to the best of their ability. They then performed 3 trials (Trials 4 to 6) where they kept the same intensity but purposefully began the breakout stroke "early", i.e. while still submerged. Following these first series of trials, the participants performed 3 separate trials (Trials 7 to 9) consciously surfacing before beginning the pull, designated the "Late Breakout". For all the trials, the subjects were instructed to keep the same effort when pushing off the wall, and perform their underwater dolphin kicks at a consistent rate and to the best of their ability

Biomechanical Motion Analysis using Software

The motion analysis software used for the data analysis (Vicon Motus Version 9) was used for camera calibration, video recording, video digitization, and kinematic analysis. Using the LED markers attached to the subject's body, it was possible to employ the automatic digitization feature in the software. In the instances that the hip marker was not visible from the lateral view due to bubbles or the motion of the arm-stroke passing the hip, the point was manually digitized. After digitization of the video trial, the software includes a feature termed "Reports", which allows the combination of video with synchronous graphing. This feature proved essential for the study as it allows for the visual tracking and identification of the pertinent phases of the underwater motions in question with graphing of hip velocity over time. Included in the reports were "Events" which identified specific time intervals during which the important phases of the breakouts were noted. The first "event" was the time frame where the pull commenced (PB), which coincided with the beginning of the downsweep motion in all 3 strokes. A second event was made to denote when time the head broke the plane of the surface, and was termed "head break" (HB). From the graphs of hip velocity the following four data points were analyzed

1. Hip velocity during the pull begin (PBV)
2. Hip velocity during the head break (HBV)
3. Maximal hip velocity during the breakout stroke (FPV)
4. Time between the pull begin and the head break (BOT)

These data points were inserted into an Excel spread sheet (Microsoft Corporation), and analyzed with SPSS software package version 20 (SPSS Inc., Chicago, IL).

Chapter 4. Results

A paired-samples *t* test was conducted to evaluate whether differences existed in the four variables: PBV, HBV, FPV, and BOT. For each variable three comparisons were made; average values from the regular trials were compared to early trials, regular compared to late, and early compared to late. This was completed for a combination of all strokes, Freestyle only, Backstroke only, and Butterfly only. A full output can be found in Appendix B. Below are the statistically significant results.

The results from the paired-samples *t* test for all strokes (Table 2) indicated that HBV was higher when swimmers performed normal their normal breakout stroke when compared to early and late breakouts. Velocity during the first pull was also higher during their regular breakout stroke. No significant difference was found between the late and early trials for PBV, HBV or FPV. The significant differences between early, regular, and late BOT show that the swimmers performed the late and early trials differently from the regular trials and different from each other.

Table 2: Paired-samples *t* test for all strokes combined

Paired Samples Test – Significant Results – Instantaneous Velocities				
Variable	Velocity (m/s)	Variable	Velocity (m/s)	Result
	Mean (SD)		Mean (SD)	
HBV Regular	1.60 (0.20)	HBV Early	1.43 (0.22)	$t(12) = 3.36, p \leq 0.01$
HBV Late	1.39 (0.19)	HBV Regular	1.60 (0.20)	$t(12) = -3.62, p \leq 0.01$
FPV Early	1.72 (0.17)	FPV Regular	1.80 (0.19)	$t(12) = -2.21, p \leq 0.05$
FPV Late	1.66 (0.20)	FPV Regular	1.80 (0.18)	$t(12) = -2.80, p \leq 0.05$

Paired Samples Test – Significant Results – Time Differential (HB-PB)				
Variable	Time (sec)	Variable	Time (sec)	Result
	Mean (SD)		Mean (SD)	

BOT Regular	0.53 (0.29)	BOT Early	0.86 (0.27)	$t(12) = -6.78$, $p \le 0.001$
BOT Late	0.05 (0.24)	BOT Early	0.86 (0.27)	$t(12) = -11.03$, $p \le 0.001$
BOT Late	0.05 (0.24)	BOT Regular	0.53 (0.29)	$t(12) = -5.86$, $p \le 0.001$

The results from a paired-samples *t*-test for freestyle trials (Table 3) indicate that PBV was lower with late breakouts than with regular. HBV for early breakouts was lower than early trials as well. BOT's for the different categories were all significantly different.

Table 3: Paired-samples *t* test for Freestyle only

Paired Samples Test – Significant Results – Instantaneous Velocities				
Variable	Velocity (m/s)	Variable	Velocity (m/s)	Result
	Mean (SD)		Mean (SD)	
PBV Late	1.32 (0.16)	PBV Regular	1.52 (0.25)	$t(4) = -4.50$, $p \le 0.05$
HBV Regular	1.62 (0.13)	HBV Early	1.39 (0.10)	$t(4) = 11.00$, $p \le 0.001$

Paired Samples Test – Significant Results – Time Differential (HB-PB)				
Variable	Time (sec)	Variable	Time (sec)	Result
	Mean (SD)		Mean (SD)	
BOT Regular	0.40 (0.21)	BOT Early	0.74 (0.11)	$t(4) = -5.70$, $p \le 0.01$
BOT Late	-0.00 (0.32)	BOT Early	0.74 (0.11)	$t(4) = -6.68$, $p \le 0.01$
BOT Late	-0.00 (0.32)	BOT Regular	0.40 (0.21)	$t(4) = -4.23$, $p \le 0.05$

The results from a paired-samples *t*-test for butterfly trials (Table 4) found no differences except for BOT. There were only two degrees of freedom.

Table 4: Paired-samples *t* test for Butterfly only

Paired Samples Test – Significant Results – Time Differential (HB-PB)				
Variable	Time (sec)	Variable	Time (sec)	Result
	Mean (SD)		Mean (SD)	
BOT Regular	0.24 (0.17)	BOT Early	0.63 (0.09)	$t(2) = -6.72$, $p \le 0.05$
BOT Late	0.08 (0.19)	BOT Early	0.63 (0.09)	$t(2) = -9.70$, $p \le 0.05$
BOT Late	0.08 (0.19)	BOT Regular	0.24 (0.17)	$t(2) = -4.64$, $p \le 0.05$

The results from a paired-samples *t*-test for backstroke trials only (Table 5) indicate a significant difference between HBV of regular and early trials. A significantly higher FPV is achieved with a regular breakout when compared to a late breakout.

Table 5: Paired samples *t* test for Backstroke only

Paired Samples Test – Significant Results – Instantaneous Velocities				
Variable	Velocity (m/s)	Variable	Velocity (m/s)	Result
	Mean (SD)		Mean (SD)	
HBV Regular	1.55 (0.15)	HBV Early	1.33 (0.18)	$t(4) = 2.73, p \leq 0.001$
FPV Late	1.53 (0.10)	FPV Regular	1.81 (0.12)	$t\ (4) = -3.63\ p \leq 0.05$

Paired Samples Test – Significant Results – Time Differential (HB-PB)				
Variable	Time (sec)	Variable	Time (sec)	Result
	Mean (SD)		Mean (SD)	
BOT Late	0.10 (0.22)	BOT Early	1.12 (0.23)	$t(4) = -13.74, p \leq 0.001$
BOT Late	0.10 (0.22)	BOT Regular	0.82 (0.11)	$t(4) = -7.10, p \leq 0.01$

A correlation matrix was established to investigate the strength of the bivariate association between the variables (Table 6). A significant, positive correlation was found between head break velocity and first pull velocity.

Table 6: Pearson Product Moment Correlation matrix determining strength of relationship between variables

	HBV	Stroke	PBV	FPV	BOT	Sex
Pearson Correlation HBV	1.00	-0.19	0.22	0.71	-0.13	-0.28
Stroke		1.00	0.38	0.23	0.64	-0.17
PBV			1.00	0.14	0.28	-0.53
FPV				1.00	0.13	-0.49
					1.00	-0.28
BOT						1.00
Sex						

A full-model simultaneous regression analysis was then conducted using the head break velocity as a dependent variable to determine the overall predictive characteristics of the variables (Table 7).

Table 7: Full-model simultaneous regression analysis method

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	1stP_Reg	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).

a. Dependent Variable: HB_Reg

Results of the simultaneous regression (Table 8) indicate that the maximal velocity during the first pull accounted for 45% of the variance in velocity at head break (R^2 = .449)

Table 8: Model summary; results of simultaneous regression

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.706[a]	.499	.449	.1543531	.499	9.960	1	10	.010

a. Predictors: (Constant), 1stP_Reg

Regression analysis was conducted for fly and back but no predictor variables were found.

Chapter 5. Discussion

The purpose of this study was to examine the kinematic variables of the breakout stroke for Freestyle, Backstroke, and Butterfly. Previously research has failed to account for how timing of the breakout stroke affected swimming speed on the surface. Takeda et al. (2009) found that initial speed during the dive or push-off did not create a difference in speed during the stroke phase. Takeda's study described the underwater kicking and stroke phase as separate but did not discuss when the pull should begin, or how long it should be until the head breaks the surface.

We hypothesized that beginning the breakout stroke too deep underwater, or after the body has reached the surface would negatively affect horizontal velocity at the moment the head breaks the surface (HBV). To test this hypothesis we had collegiate swimmers perform normal breakouts at the best of their ability, breakouts where the breakout time (between the beginning of the pull and when the head broke the surface) was elongated, and where breakout timing that was shortened. Filming was done using high-speed videography equipment. The data was analyzed using Motus 9 motion analysis software.

We found that the average breakout time was 0.40 ± 0.22 (n=5) for Freestyle, 0.82±0.11 (n=5) for Backstroke, and 0.25±0.17 (n=3) for Butterfly during normal breakout trials. When analyzing all subjects across all three strokes there were significant differences in HBV. When swimmers performed early breakouts their breakout times were significantly higher ($p \leq 0.001$) and significantly lower with late breakouts ($p \leq 0.001$).

Pull Begin

The only significant difference found in the hip velocity when the pull began was between late and regular trials for Freestyle only. The difference is likely caused by the wave drag created by the swimmer when they are near the surface. If a swimmer spends more time encountering wave drag without the additional propulsion from the arm-stroke they will slow down. The lack of significant difference in Butterfly and Backstroke is possibly due to the low enrollment.

First Pull

Statistically significant differences in the maximal hip velocity of the first pull (FPV) were found when regular timing was compared to late and early timing when all strokes were combined. Hip velocity during regular timing (1.80±.19 m/s) was great than late timing (1.67±0.20 m/s, $p \leq 0.05$) and greater than early timing (1.72±0.17 m/s, $p \leq 0.05$).

Significant differences were also found when Backstroke was isolated. First pull hip velocity was greater with regular breakout timing (1.81±0.12 m/s) than with late timing (1.53±0.10 m/s, $p \leq 0.05$). This is possibly caused by the extended time the swimmer was on or close to the surface encountering wave drag before gaining propulsion from the pulling action.

Head Break

Hip velocity at the moment the head breaks the surface (HBV) describes how fast the swimmer is traveling when beginning the surface swimming phase of the length.

When all swimmers and strokes were combined there was significant difference in HBV value when regular breakout timing was compared to late and early timing. For all strokes, hip velocity was greater for HBV for regular timing (1.60±0.20 m/s) when compared to late (1.39±0.19 m/s, $p \leq 0.01$) and early (1.43±0.22 m/s, $p \leq 0.01$). When late timing was used, the swimmer may have slowed down due to prolonged underwater kicking resulting in speeds below their surface swimming speed. They may also have encountered some wave drag near the surface without the additional propulsion of the armstroke. With early timing, the swimmer's first pull was taken while completely submerged and then the swimmer 'glided' to the surface with lack of additional propulsion, likely causing the velocity to decrease by the moment the head broke through the surface.

Significant differences in HBV were found when Freestyle was isolated between regular breakouts and early breakouts. Hip velocity was greater for HBV for regular timing (1.62±0.13m/s) when compared to early timing (1.39±0.10, $p \leq 0.001$). Differences in Backstroke between early (1.55±0.15 m/s) and regular (1.33±0.18, $p \leq 0.001$) breakouts are similar to freestyle.

Regression analysis showed that among regular trials the velocity during the first pull (FPV) was the biggest indicator of head break velocity (HBV). This is logical because a swimmer who has a stronger first pull will likely be able to propel the head through the surface at a higher velocity.

We found that wave drag played a role in all the strokes, but we are not sure why there was no difference in the individual strokes.

Possible Changes in Drag Profile during the Breakout Stroke

It is not known how exactly a swimmer determines when to begin their breakout stroke. When the swimmer approaches the surface, toward the end of their underwater kicking, they must make a judgment of when is optimal to begin their breakout stroke. If the swimmer positions their head in a position to look directly at the surface while swimming on their stomach they will increase form drag (Zaidi, Taiar, Fohanno, & Polidori, 2008). For this reason, the swimmer must look down through the breakout motion in Freestyle and Butterfly. Swimmers likely determine their depth from mechanoreceptor feedback due to the decrease in pressure as they near the surface. Swimmers likely also determine depth visually by judging how far they are from the bottom of the pool, though this may change from pool to pool giving some swimmers a “home court advantage”. Though no studies as of yet have determined when is optimal, we hope this study sheds light on the importance of correct timing. We have shown that taking the stroke when too deeply submerged will cause the swimmer to decelerate when their arms are forced to recover forward while underwater, causing great amounts of excess form drag. We have also shown that if the swimmer waits too long to being their breakout stroke, causing them to surface, they will begin to create wave drag on the surface without added propulsion from the arms to overcome the drag and will decelerate as well.

Chapter 6. Practical Applications and Future Research

The breakout stroke presents an opportunity to gain a competitive advantage for swimmers. The current study shows that the timing of the breakout is essential to maintaining momentum from the underwater kicking phase to the stroke phase and that improper timing can be detrimental to speed at head break. When swimming the Freestyle and Backstroke, taking the breakout stroke too early, or when the body is positioned too far under the surface, was more detrimental to HBV than when swimmers took the breakout stroke too late or when the body was positioned too close to the surface. This information is important to coaches when assessing the ramifications of the two variations that result in less than optimum hip velocities during the breakout.

Future research is needed to create an index of what is the optimal timing for the breakout stroke in each swimming discipline. With more participants and fewer alterations in technique, it may be possible to derive an equation for what breakout time (BOT) is most effective. Stroke rate may also be examined as a contributing factor. Further study could provide an indication if HBV is an important factor in speed throughout the stroke phase.

Appendix A: Consent Form

University of Hawai'i
Consent to Participate in Research Project:

Analysis of breakout stroke variations during freestyle, backstroke, and butterfly swimming

My name is Stephen Allnutt. I am a graduate student at the University of Hawaii at Manoa in the Department of Kinesiology. As part of the requirements for earning my graduate degree, I am doing a research project as a requirement for earning my graduate degree. The purpose of my project is to evaluate the effectiveness of different stroke timing variations during the breakout stroke for freestyle, backstroke, and butterfly swimming. I am asking you to participate because you were filmed by Dr. Prins in the Aquatic Research Lab during your time on the UH swim team between 2011 and 2012

Activities and Time Commitment: I am asking for your permission to use video tapes of your swimming that were previously filmed by the UH Swim Team between January 2011 and December 2012. These videos show you performing your breakout stroke. This research will not require any additional time commitment from you. You will be one of about 18 people whose videos I will review for this study.

Benefits and Risks: There will be no direct benefit to you for participating in this research project. The results of this project may help add to the general collection of swimming knowledge about breakouts. If you would like to review your video for your benefit then you may contact me or Dr. Prins and set up an appointment. I believe there is little risk to you in participating in this research project. If you feel that your privacy is being violated or you would like us not to review your video at any point you may opt-out of the research project without any consequences.

Privacy and Confidentiality: I will keep all information in a safe place on a password protected computer in a locked office. Only my University of Hawaii advisor and I will have access to the information. Other agencies that have legal permission have the right to review research records. The University of Hawaii Human Studies Program has the right to review research records for this study. When I report the results of my research project, I will not use your name. I will not use any other personal identifying information that can identify you, unless you give your consent. If you choose to give consent to use your picture and video when the research is published you can designate that on this form. I will use report my findings in a way that protects your privacy and confidentiality to the extent allowed by law.

Voluntary Participation: Your participation in this project is completely voluntary. You may stop participating at any time. If you stop being in the study, there will be no penalty or loss to you.

If you agree to participate in this project, please sign and date this signature page and return it to:

Stephen Allnutt, Principal Investigator at: [allnutt@hawaii.edu, 808-956-6040]

Signature:

I have read and understand the information provided to me about being in the research project, *Analysis of breakout stroke variations during freestyle, backstroke, and butterfly swimming*

My signature below indicates that I agree to participate in this research project.

Printed name: ______________________________

Signature: _________________________________

Date: ______________________________

My signature below indicates that I agree to allow use of my videos and pictures when publishing research. (No names will be disclosed).

Signature: __________________________________

You will be given a copy of this consent form for your records.

Appendix B: Paired Samples *t*-test Results

Table 9. Paired Samples *t*-test – All strokes combined

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	PB_Reg	1.557317	10	.3704265	.1171391
	PB_Early	1.476083	10	.4060161	.1283936
Pair 2	PB_Late	1.392818	11	.6892525	.2078174
	PB_Early	1.340803	11	.5913311	.1782930
Pair 3	PB_Late	1.446139	12	.5799064	.1674045
	PB_Reg	1.579125	12	.3396324	.0980434
Pair 4	HB_Reg	1.603077	13	.1999084	.0554446
	HB_Early	1.432282	13	.2163330	.0600000
Pair 5	HB_Late	1.391538	13	.1882115	.0522005
	HB_Early	1.432282	13	.2163330	.0600000
Pair 6	HB_Late	1.391538	13	.1882115	.0522005
	HB_Reg	1.603077	13	.1999084	.0554446
Pair 7	1stP_Early	1.716090	13	.1731315	.0480180
	1stP_Reg	1.799577	13	.1858152	.0515359
Pair 8	1stP_Late	1.662269	13	.1977195	.0548375
	1stP_Early	1.716090	13	.1731315	.0480180
Pair 9	1stP_Late	1.662269	13	.1977195	.0548375
	1stP_Reg	1.799577	13	.1858152	.0515359
Pair 10	t2t1_Reg	.527026	13	.2938826	.0815084
	t2t1_Early	.862615	13	.2656881	.0736886
Pair 11	t2t1_Late	.054705	13	.2394306	.0664061
	t2t1_Early	.862615	13	.2656881	.0736886
Pair 12	t2t1_Late	.054705	13	.2394306	.0664061
	t2t1_Reg	.527026	13	.2938826	.0815084

Table 9. (Continued) Paired Samples *t*-test – All strokes combined

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	PB_Reg - PB_Early	.081	.1568680	.0496060	-.0309833	.1934500	1.638	9	.136
Pair 2	PB_Late - PB_Early	.052	.2696425	.0813003	-.1291332	.2331635	.640	10	.537
Pair 3	PB_Late - PB_Reg	-.132	.3456274	.0997740	-.3525873	.0866151	-1.333	11	.210
Pair 4	HB_Reg - HB_Early	.170	.1831273	.0507904	.0601322	.2814576	3.363	12	.006
Pair 5	HB_Late - HB_Early	-.040	.2420054	.0671202	-.1869860	.1054988	-.607	12	.555
Pair 6	HB_Late - HB_Reg	-.211	.2106635	.0584276	-.3388412	-.0842358	-3.621	12	.004
Pair 7	1stP_Early - 1stP_Reg	-.083	.1359472	.0377050	-.1656392	-.0013351	-2.214	12	.047
Pair 8	1stP_Late - 1stP_Early	-.053	.1473372	.0408640	-.1428555	.0352145	-1.317	12	.212
Pair 9	1stP_Late - 1stP_Reg	-.137	.1765542	.0489673	-.2439984	-.0306170	-2.804	12	.016
Pair 10	t2t1_Reg - t2t1_Early	-.335	.1786627	.0495521	-.4435546	-.2276249	-6.772	12	.000
Pair 11	t2t1_Late - t2t1_Early	-.807	.2641902	.0732732	-.9675588	-.6482617	-11.026	12	.000
Pair 12	t2t1_Late - t2t1_Reg	-.472	.2908083	.0806557	-.6480542	-.2965868	-5.856	12	.000

Table 10. Paired Samples *t*-test – Freestyle only

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	PB_Reg	1.515150	5	.2466499	.1103052
	PB_Early	1.408700	5	.1205104	.0538939
Pair 2	PB_Late	1.317167	5	.1563507	.0699221
	PB_Early	1.408700	5	.1205104	.0538939
Pair 3	PB_Late	1.317167	5	.1563507	.0699221
	PB_Reg	1.515150	5	.2466499	.1103052
Pair 4	HB_Reg	1.621500	5	.1251290	.0559594
	HB_Early	1.385467	5	.1001623	.0447940
Pair 5	HB_Late	1.434133	5	.2415388	.1080194
	HB_Early	1.385467	5	.1001623	.0447940
Pair 6	HB_Late	1.434133	5	.2415388	.1080194
	HB_Reg	1.621500	5	.1251290	.0559594
Pair 7	1stP_Early	1.666367	5	.0531226	.0237571
	1stP_Reg	1.744983	5	.1125581	.0503375
Pair 8	1stP_Late	1.649400	5	.1124237	.0502774
	1stP_Early	1.666367	5	.0531226	.0237571
Pair 9	1stP_Late	1.649400	5	.1124237	.0502774
	1stP_Reg	1.744983	5	.1125581	.0503375
Pair 10	t2t1_Reg	.399400	5	.2150042	.0961528
	t2t1_Early	.741400	5	.1112945	.0497724
Pair 11	t2t1_Late	-.002867	5	.3169306	.1417357
	t2t1_Early	.741400	5	.1112945	.0497724
Pair 12	t2t1_Late	-.002867	5	.3169306	.1417357
	t2t1_Reg	.399400	5	.2150042	.0961528

Table 10. (Continued) Paired Samples *t*-test – Freestyle only

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	PB_Reg - PB_Early	.106	.1885813	.0843361	-.1277046	.3406046	1.262	4	.275
Pair 2	PB_Late - PB_Early	-.091	.1390212	.0621721	-.2641509	.0810842	-1.472	4	.215
Pair 3	PB_Late - PB_Reg	-.197	.0985610	.0440778	-.3203630	-.0756036	-4.492	4	.011
Pair 4	HB_Reg - HB_Early	.236	.0479755	.0214553	.1764639	.2956027	11.001	4	.000
Pair 5	HB_Late - HB_Early	.048	.1995982	.0892630	-.1991673	.2965006	.545	4	.615
Pair 6	HB_Late - HB_Reg	-.187	.2217034	.0991488	-.4626478	.0879145	-1.890	4	.132
Pair 7	1stP_Early - 1stP_Reg	-.078	.0844709	.0377766	-.1835012	.0262679	-2.081	4	.106
Pair 8	1stP_Late - 1stP_Early	-.016	.0943310	.0421861	-.1340941	.1001607	-.402	4	.708
Pair 9	1stP_Late - 1stP_Reg	-.095	.0825553	.0369199	-.1980893	.0069226	-2.589	4	.061
Pair 10	t2t1_Reg - t2t1_Early	-.342	.1343472	.0600819	-.5088141	-.1751859	-5.692	4	.005
Pair 11	t2t1_Late - t2t1_Early	-.744	.2493150	.1114971	-1.0538321	-.4347012	-6.675	4	.003
Pair 12	t2t1_Late - t2t1_Reg	-.402	.2127528	.0951459	-.6664341	-.1380992	-4.228	4	.013

Table 11. Paired Samples *t*-test – Butterfly only

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	PB_Reg	1.371556	3	.2042472	.1179222
	PB_Early	1.326111	3	.2232252	.1288791
Pair 2	PB_Late	1.335444	3	.1617352	.0933778
	PB_Early	1.326111	3	.2232252	.1288791
Pair 3	PB_Late	1.335444	3	.1617352	.0933778
	PB_Reg	1.371556	3	.2042472	.1179222
Pair 4	HB_Reg	1.648444	3	.3944949	.2277618
	HB_Early	1.684889	3	.2609160	.1506399
Pair 5	HB_Late	1.430889	3	.1806938	.1043236
	HB_Early	1.684889	3	.2609160	.1506399
Pair 6	HB_Late	1.430889	3	.1806938	.1043236
	HB_Reg	1.648444	3	.3944949	.2277618
Pair 7	1stP_Early	1.868222	3	.2847604	.1644065
	1stP_Reg	1.867778	3	.3697207	.2134583
Pair 8	1stP_Late	1.900111	3	.2548530	.1471394
	1stP_Early	1.868222	3	.2847604	.1644065
Pair 9	1stP_Late	1.900111	3	.2548530	.1471394
	1stP_Reg	1.867778	3	.3697207	.2134583
Pair 10	t2t1_Reg	.249889	3	.1744325	.1007087
	t2t1_Early	.630667	3	.0933881	.0539176
Pair 11	t2t1_Late	.080556	3	.1910085	.1102788
	t2t1_Early	.630667	3	.0933881	.0539176
Pair 12	t2t1_Late	.080556	3	.1910085	.1102788
	t2t1_Reg	.249889	3	.1744325	.1007087

Table 11. (Continued) Paired Samples *t*-test – Butterfly only

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	PB_Reg - PB_Early	.045	.0597051	.0344708	-.1028713	.1937602	1.318	2	.318
Pair 2	PB_Late - PB_Early	.009	.1580425	.0912459	-.3832661	.4019328	.102	2	.928
Pair 3	PB_Late - PB_Reg	-.036	.1874283	.1082118	-.5017088	.4294866	-.334	2	.770
Pair 4	HB_Reg - HB_Early	-.036	.2052317	.1184906	-.5462682	.4733793	-.308	2	.787
Pair 5	HB_Late - HB_Early	-.254	.1444484	.0833973	-.6128297	.1048297	-3.046	2	.093
Pair 6	HB_Late - HB_Reg	-.217	.3427471	.1978851	-1.0689866	.6338755	-1.099	2	.386
Pair 7	1stP_Early - 1stP_Reg	.000	.0982312	.0567138	-.2435754	.2444643	.008	2	.994
Pair 8	1stP_Late - 1stP_Early	.031	.0312984	.0180702	-.0458608	.1096385	1.765	2	.220
Pair 9	1stP_Late - 1stP_Reg	.032	.1204233	.0695264	-.2668148	.3314815	.465	2	.688
Pair 10	t2t1_Reg - t2t1_Early	-.380	.0980965	.0566360	-.6244630	-.1370925	-6.723	2	.021
Pair 11	t2t1_Late - t2t1_Early	-.550	.0985452	.0568951	-.7949109	-.3053114	-9.669	2	.011
Pair 12	t2t1_Late - t2t1_Reg	-.169	.0631858	.0364803	-.3262955	-.0123711	-4.642	2	.043

Table 12. Paired Samples *t*-test – Backstroke only

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	PB_Reg	1.941375	2	.7076371	.5003750
	PB_Early	1.869500	2	.9623723	.6805000
Pair 2	PB_Late	1.576278	3	1.4935072	.8622768
	PB_Early	1.242333	3	1.2818324	.7400663
Pair 3	PB_Late	1.690375	4	1.0312731	.5156365
	PB_Reg	1.814771	4	.4359809	.2179905
Pair 4	HB_Reg	1.557433	5	.1478094	.0661024
	HB_Early	1.327533	5	.1789306	.0800202
Pair 5	HB_Late	1.325333	5	.1506536	.0673743
	HB_Early	1.327533	5	.1789306	.0800202
Pair 6	HB_Late	1.325333	5	.1506536	.0673743
	HB_Reg	1.557433	5	.1478094	.0661024
Pair 7	1stP_Early	1.674533	5	.1547576	.0692097
	1stP_Reg	1.813250	5	.1229554	.0549873
Pair 8	1stP_Late	1.532433	5	.0919764	.0411331
	1stP_Early	1.674533	5	.1547576	.0692097
Pair 9	1stP_Late	1.532433	5	.0919764	.0411331
	1stP_Reg	1.813250	5	.1229554	.0549873
Pair 10	t2t1_Reg	.820933	5	.1082578	.0484143
	t2t1_Early	1.123000	5	.2270606	.1015446
Pair 11	t2t1_Late	.096767	5	.2154952	.0963724
	t2t1_Early	1.123000	5	.2270606	.1015446
Pair 12	t2t1_Late	.096767	5	.2154952	.0963724
	t2t1_Reg	.820933	5	.1082578	.0484143

Table 12. (Continued) Paired Samples *t*-test – Backstroke only

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	PB_Reg - PB_Early	.071	.2547352	.1801250	-2.2168301	2.3605801	.399	1	.758
Pair 2	PB_Late - PB_Early	.333	.3555700	.2052884	-.5493403	1.2172292	1.627	2	.245
Pair 3	PB_Late - PB_Reg	-.124	.6205785	.3102892	-1.1118747	.8630830	-.401	3	.715
Pair 4	HB_Reg - HB_Early	.229	.1880085	.0840799	-.0035434	.4633434	2.734	4	.052
Pair 5	HB_Late - HB_Early	-.002	.2819028	.1260708	-.3522286	.3478286	-.017	4	.987
Pair 6	HB_Late - HB_Reg	-.232	.1547941	.0692260	-.4243023	-.0398977	-3.353	4	.028
Pair 7	1stP_Early - 1stP_Reg	-.138	.1853618	.0828963	-.3688737	.0914404	-1.673	4	.170
Pair 8	1stP_Late - 1stP_Early	-.142	.1969460	.0880769	-.3866407	.1024407	-1.613	4	.182
Pair 9	1stP_Late - 1stP_Reg	-.280	.1730453	.0773882	-.4956808	-.0659525	-3.629	4	.022
Pair 10	t2t1_Reg - t2t1_Early	-.302	.2644105	.1182480	-.6303757	.0262423	-2.555	4	.063
Pair 11	t2t1_Late - t2t1_Early	-1.026	.1669917	.0746809	-1.2335809	-.8188858	-13.742	4	.000
Pair 12	t2t1_Late - t2t1_Reg	-.724	.2284294	.1021567	-1.0077993	-.4405341	-7.089	4	.002

Appendix C: Stepwise Linear Regression Results

Table 13. Regression Analysis – All Swimmers and all strokes combined

Table 13. Part 1

Descriptive Statistics

	Mean	Std. Deviation	N
HB_Reg	1.598000	.2079203	12
Stroke	1.92	.900	12
PB_Reg	1.579125	.3396324	12
1stP_Reg	1.806958	.1920766	12
t2t1_Reg	.511944	.3016505	12
Sex	1.25	.452	12

Table 13. Part 2

Correlations

		HB_Reg	Stroke	PB_Reg	1stP_Reg	t2t1_Reg	Sex
Pearson Correlation	HB_Reg	1.000	-.188	.217	.706	-.128	-.278
	Stroke	-.188	1.000	.375	.230	.640	-.167
	PB_Reg	.217	.375	1.000	.140	.281	-.533
	1stP_Reg	.706	.230	.140	1.000	.130	-.489
	t2t1_Reg	-.128	.640	.281	.130	1.000	-.284
	Sex	-.278	-.167	-.533	-.489	-.284	1.000
Sig. (1-tailed)	HB_Reg	.	.280	.249	.005	.346	.190
	Stroke	.280	.	.115	.236	.013	.301
	PB_Reg	.249	.115	.	.332	.188	.037
	1stP_Reg	.005	.236	.332	.	.344	.054
	t2t1_Reg	.346	.013	.188	.344	.	.186
	Sex	.190	.301	.037	.054	.186	.
N	HB_Reg	12	12	12	12	12	12
	Stroke	12	12	12	12	12	12
	PB_Reg	12	12	12	12	12	12
	1stP_Reg	12	12	12	12	12	12
	t2t1_Reg	12	12	12	12	12	12
	Sex	12	12	12	12	12	12

Table 13. Part 3

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	1stP_Reg	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).

a. Dependent Variable: HB_Reg

Table 13. Part 4

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.706[a]	.499	.449	.1543531	.499	9.960	1	10	.010

a. Predictors: (Constant), 1stP_Reg

Table 13. Part 5

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.237	1	.237	9.960	.010[b]
	Residual	.238	10	.024		
	Total	.476	11			

a. Dependent Variable: HB_Reg

b. Predictors: (Constant), 1stP_Reg

Table 13. Part 6

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.216	.440		.491	.634
	1stP_Reg	.765	.242	.706	3.156	.010

a. Dependent Variable: HB_Reg

Table 13. Part 7

Excluded Variables[a]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics
						Tolerance
1	Stroke	-.370[b]	-1.770	.111	-.508	.947
	PB_Reg	.120[b]	.511	.621	.168	.980
	t2t1_Reg	-.223[b]	-.987	.349	-.313	.983
	Sex	.088[b]	.326	.752	.108	.761

a. Dependent Variable: HB_Reg

b. Predictors in the Model: (Constant), 1stP_Reg

References

Atkison, R. R., Dickey, J. P., Dragunas, A., & Nolte, V. (2013). Importance of sagittal kick symmetry for underwater dolphin kick performance. *Human movement science*.

Barbosa, T. M., Lima, F., Portela, A., Novais, D., Machado, L., Colaço, P., & Vilas-Boas, J. P. (2006). Relationships between energy cost, swimming velocity and speed fluctuation in competitive swimming strokes.

Barbosa, T. M., Keskinen, K. L., Fernandes, R., Colaço, P., Lima, A. B., & Vilas-Boas, J. P. (2005). Energy cost and intracyclic variation of the velocity of the centre of mass in Butterfly stroke. *European Journal of Applied Physiology*,*93*(5-6), 519-523.

Ceseracciu, E., Sawacha, Z., Fantozzi, S., Cortesi, M., Gatta, G., Corazza, S., & Cobelli, C. (2011). Markerless analysis of front crawl swimming. *Journal of biomechanics*, *44*(12), 2236-2242.

Craig, A. B., Termin, B., & Pendergast, D. R. (2006). Simultaneous recordings of velocity and video during swimming. *Portuguese Journal of Sport Sciences*,*6*(2), 32-35.

Dempster, W. T. (1955). Space requirements of the seated operator: geometrical, kinematic, and mechanical aspects of the body, with special reference to the limbs.

Honda, K., Keys, M., Lyttle, A., Alderson, J., Bennamoun, M., & El-Sallam, A. (2012). Freestyle swimming: an insight into propulsive and resistive mechanisms. In *ISBS-Conference Proceedings Archive* (Vol. 1, No. 1).

Kiran, D., Carlson, M., Medrano Jr, D., & Smith, D. R. (2010). Validity of two dimensional vicon motus software at varying camera angles. *In International Journal of Exercise Science: Conference Proceedings* (Vol. 4, No. 1, p. 9).

Lyttle, A. D., Blanksby, B. A., Elliott, B. C., & Lloyd, D. G. (1998). The effect of depth and velocity on drag during the streamlined glide. *Journal of Swimming Research*, *13*.

Nigg, B. (1983). Selected methodology in biomechanics with respect to swimming *Biomechanics and medicine in swimming*, 72-80.

Novais, M., Silva, A., Mantha, V., Ramos, R., Rouboa, A., Vilas-Boas, J., & Marinho, D. (2012). The Effect of Depth on Drag During the Streamlined Glide: A Three-Dimensional CFD Analysis. *Journal of human kinetics*, *33*(1), 55-62.

Maglischo, E. W. (2003). *Swimming fastest*. Human Kinetics.

Rushall, B. S., Sprigings, E. J., Holt, L. E., & Cappaert, J. M. (1994). A re-evaluation of forces in swimming. *Journal of Swimming Research*, *10*, 6-30.

Shimadzu, H., Shibata, R., & Ohgi, Y. (2008). Modelling swimmers' speeds over the course of a race. *Journal of biomechanics*, *41*(3), 549-555.

Sweetenham, B., & Atkinson, J. (2003). *Championship swim training* (Vol. 1). Human Kinetics.

Takeda, T., Ichikawa, H., Takagi, H., & Tsubakimoto, S. (2009). Do differences in initial speed persist to the stroke phase in front-crawl swimming?. *Journal of sports sciences*, *27*(13), 1449-1454.

Tella, V., Toca-Herrera, J. L., Gallach, J. E., Benavent, J., González, L. M., & Arellano, R. (2008). Effect of fatigue on the intra-cycle acceleration in front crawl swimming: A time–frequency analysis. *Journal of biomechanics*, *41*(1), 86-92.

Toussaint, H., & Truijens, M. (2005). Biomechanical aspects of peak performance in human swimming. *Animal Biology*, *55*(1), 17-40.

Vennell, R., Pease, D., & Wilson, B. (2006). Wave drag on human swimmers. *Journal of biomechanics*, *39*(4), 664-671.

von Loebbecke, A., Fish, F., Mark, R., & Mittal, R. (2009). Propulsive efficiency of the underwater dolphin kick in humans. *Journal of biomechanical engineering*, *131*(5), 054504.

Zaidi, H., Taiar, R., Fohanno, S., & Polidori, G. (2008). Analysis of the effect of swimmer's head position on swimming performance using computational fluid dynamics. *Journal of Biomechanics*, *41*(6), 1350-1358.