KINEMATIC ANALYSIS OF PEAK VELOCITIES IN THE BREASTSTROKE AS A FUNCTION OF THE TIMING OF THE KICK

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

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By

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Abstract

The purpose of this study was to determine the effects of the timing of the Breaststroke kick on intra-cyclic velocity fluctuations. Researchers examined peak hip velocities of Breaststroke swimmers to determine any significant velocity drop-offs and magnitude of velocity regained between different kicking techniques. Subjects performed swimming trials with three different kick protocols: a conventional stroke, a late kick, and a delayed late kick. Video analysis was used to analyze peak and minimum hip velocities within one Breaststroke cycle for each trial. Data was analyzed using ANOVA repeated measures analysis. Major findings of this study were that due to smaller percentages of hip velocity drop-off, higher swimming velocities may be achieved when the kick is initiated during the insweep or early recovery arm phases and that video analysis and verbal cueing are viable tools to help swimmers improve their regular stroke technique.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

%VDO	Percentage Velocity Drop-off
%VR	Percentage of Velocity Regained
ANOVA	Analysis of Variance
C100	Conventional Stroke 100-yard sprint pace
CFD	Computation Fluid Dynamics
CI	Confidence Interval
DU1	Late Kick
DU2	Delayed Late Kick
LED	Light-Emitting Diode
MKF	Maximal Knee Flexion Angle
NCAA	National Collegiate Athletic Association
PAV	Maximum Hip Velocity Generated by the Arms
PLV	Maximum Hip Velocity Generated by the Legs
SD	Standard Deviation
SPSS	Statistical Package for the Social Sciences
TCK	Time to Complete Kick
UH	University of Hawaiʻi at Mānoa

KINEMATIC ANALYSIS OF PEAK VELOCITIES IN THE BREASTSTROKE AS A FUNCTION OF THE TIMING OF THE KICK

Introduction

The Breaststroke can be broken down into three phases, the Kick, the Pull, and the Glide. When these three phases are completed in succession, a swimmer has completed one full cycle of the Breaststroke. The variations in the overall swimming velocity throughout one Breaststroke cycle are a good indicator of the swimmer's stroke efficiency; the more efficient a swimmer's stroke is, the better they will perform (Takagi, Sugimoto, Nishijima, & Wilson, 2004). A number of current studies have examined the coordination of the arms and the legs during the Breaststroke cycle (C. D. D'Acquisto LJ, 1998; Leblanc, Seifert, & Chollet, 2009; van Houwelingen, Roerdink, Huibers, Evers, & Beek, 2017). The earlier studies mainly focus on periods of propulsion provided by each phase and how they affect the acceleration and deceleration of the entire cycle. The most recent study by van Houwelingen et al. noted swimmers are capable of manipulating their arm-leg coordination resulting in intra-cyclic velocity variations. However, their results were inconclusive.

During the 2016 Olympics, British swimmer Adam Peaty won the men's 100-meter Breaststroke race in world-record fashion using a kick technique that performs the kick phase of the Breaststroke later than it is conventionally taught. To our knowledge, there is currently no research that examines how the timing of the initiation of the kick, when occurring during different phases of arm pull can affect the propulsion, acceleration, and consequently intra-cyclic velocity of the Breaststroke.

The lack of research regarding analysis of the timing of the Breaststroke kick is likely due the relatively new nature of this technique. However, given the surprising effect this technique has had on Adam Peaty's gold-medal, world-record performance at the 2016 Olympic games, it is clear that this technique should be investigated to determine if his performances were the result of training, or improved technique.

Kinematic analysis provides invaluable information for both swimmers and coaches; video playback allows them to immediately review a swimmer's technique and obtain feedback for making corrections, and digital analysis allows a swimmer's stroke efficiency to be formally evaluated and improved (Costa et al., 2010; C. D. D'Acquisto LJ, 1998; C. D. D'Acquisto LJ, Gehtsen GM, Wong-Tai Y, Lee G, 1988; Jaszczak, 2011; Strzała et al., 2012). The hip has been validated as the most reliable anatomical landmark to use for measuring intra-cyclic velocity and its changes within a stroke; the frame-by-frame analysis that can be utilized in accompaniment with the recorded intra-cyclic velocity fluctuations allows researchers to pinpoint which aspects of the technique are contributing to the fluctuations in order to make improvements (Costa et al., 2010; C. D. D'Acquisto LJ, 1998; C. D. D'Acquisto LJ, Gehtsen GM, Wong-Tai Y, Lee G, 1988; Jaszczak, 2011; Strzała et al., 2012; van Houwelingen et al., 2017).

Need for the Study

Currently there are no published studies that examine the effects of the timing of the Breaststroke kick during specific pull phases on intra-cyclic velocity fluctuations. The expectation is that this research can lead to improved stroke efficiency and consequently faster swimming times.

Statement of the Problem

The purpose of the study is to determine the effects of the timing of the Breaststroke kick on intra-cyclic velocity fluctuations. The expectation is that through this investigation it can be determined if the timing associated with a "late kick" can provide higher overall swimming speeds than the "conventional kick" technique.

Methods

Study Objectives

The purpose of this study was to describe the results of a kinematic analysis of the "conventional" vs. "late" Breaststroke kick, using selected variables of these two types of kick patterns. The study was divided into two elements, each posing the following questions:

Question 1: Is there a significant difference in peak hip velocity drop-offs between the two techniques (conventional vs. late) of Breaststroke kicking?

Hypothesis 1: There will be a significant difference between the two techniques of kicking – there will be less of a drop-off in peak hip velocity for the subjects who utilize the late kick technique.

Question 2: Is there a significant difference in the percentage of velocity regained during the propulsive phase of the kick related to the magnitude of velocity percentage drop-off during kick deceleration?

Hypothesis 2: There will be a significant difference in the percentage of velocity regained during the propulsive phase of the kick related to the magnitude of velocity percentage drop-off – the smaller the percentage velocity drop-off, the greater the percentage of velocity regained will be.

Research Design

This study utilized a single-subject design by examining the effects on peak velocity during the Breaststroke with three different trials of executing the kick during different phases of the stroke. The independent variable was the timing of the kick (conventional, late, or delayed late) and the dependent variables were maximal knee flexion angle, peak arm velocity, peak leg velocity, time to complete kick, percentage of velocity drop-off, and percentage of velocity regained.

Participants

Subjects were recruited from an NCAA Division I swimming team (4 males & 5 females). n=9 subjects (G*Power a priori analysis: ANOVA repeated measures, within factors; effect size f= 0.5; p=0.05; power= 0.8; number of groups= 1; number of measurements= 3; correlation among repeated measures= 0.5; non-sphericity correction = 1)

Inclusionary criteria: Breaststroke must be one of their primary competitive events; they must have reached NCAA Division I levels of competitive experience.

Exclusionary criteria: Non-experienced competitive swimmers; injury that prevents swimmer from swimming with normal technique; Breaststroke is not a primary race event for the swimmer.

Performance Site

This study was performed at the Duke Kahanamoku Aquatic Complex, on the campus of the University of Hawaiʻi – Mānoa.

Instruments

- Three high-speed digital cameras (Baumer Model HXG with CMOS sensors), installed in custom housings (The Sexton Company, Salem, Oregon).

- All 3 housings were attached to custom-designed mounting frames and positioned so as to provide the three required fields of view (Figure 1).

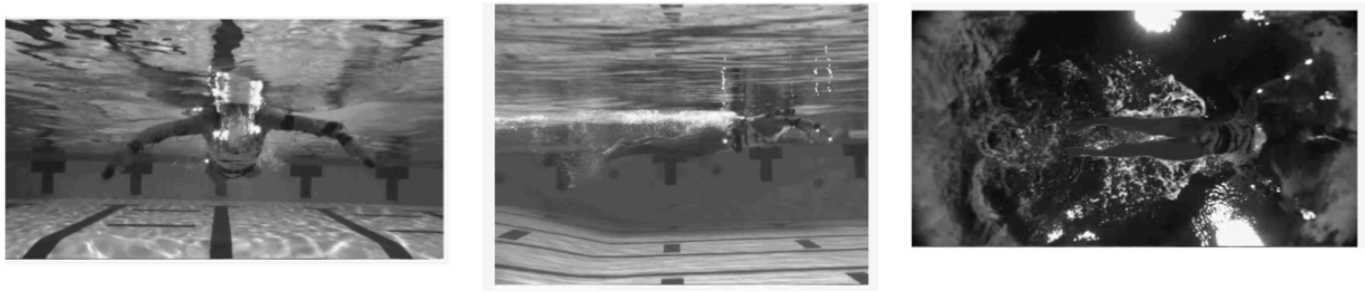

Figure 1. Synchronized frames of the three camera angles used to film swimming trials.

- Camera 1 was used for recording the frontal, or head-on view, of the subject's progress and was mounted on a vertically oriented frame. The camera was positioned at a depth of 0.48 meters (1.57 feet).

- Camera 2 was mounted on a horizontal platform that rested on the bottom of the pool at a depth of 2.13 meters (7 feet). The camera was aligned vertically, i.e.

pointing upwards to the surface and provided a transverse view of the subject's progress.

- Camera 3 was mounted on a laterally positioned frame that was bolted to the concrete deck of the pool. The camera was positioned at a depth of 0.48 meters (1.57 feet), similar to the depth of Camera 1. The lateral orientation of Camera 3 provided the data for the progress of the subject in the longitudinal plane of motion.

- The distance the subject was required to cover in each trial varied between 11.89 and 13.71 meters (39 to 45 feet). This distance was determined by placing the camera that was used for recording the frontal, or head-on view of the subject at a distance of 13.71 meters (45 feet) yards from the side of the pool from which the subject was required to push-off at the start of each trial. Subjects were instructed to swim directly towards this camera, approaching it as close as possible without colliding with the camera.

- The cameras were controlled via dual 9.14 meter-long (30 feet) Gigabit (GigE) Ethernet cables connected to a desktop computer located on the pool deck. Each camera had two cables - one cable was assigned to camera control and another cable was used for frame synchronization. Unlike the limitations relating to maximum functional lengths inherent when using Firewire cabling, GigE cabling does not have a length restriction, which allowed for optimum placement of the underwater cameras in the pool.

- Rotational joint segments were identified using a custom-designed string of light emitting diodes (LED's), housed in waterproof housings. The LED's were duct taped to the body and powered by a battery pack attached to a belt worn by the subject at the waist.

- Templo (Contemplas, Kempten, Germany) motion capture software was used for capturing and recording the video data.

- A second software package, Motus, (Contemplas, Kempten, Germany), was used for digitizing, data analysis, and generating "reports". This software included a "Multi 2-D" (M2-D) feature, which enabled multiple cameras to be synchronized. Each sequence was digitized using a combination of auto-tracking and manual modes.

- IBM Statistical Package for the Social Sciences (SPSS) version 23 was used to run statistical analysis.

Kinematic Data Collection Procedures

After obtaining approval for the study from the University of Hawai'i at Mānoa University Institutional Review Board for the Study of Human Subjects, Breaststroke subjects were recruited from the University of Hawai'i at Mānoa Intercollegiate Swimming Team. Subjects reported to the pool at a scheduled time, and signed a consent form. Prior to videotaping, each subject was shown a previously digitized swim trial so as to familiarize them with the outcome of the videotaping and resulting "report. " Following the recording of each subject's anthropometric data, the LED lights were taped on to specific anatomic landmarks (bilateral fingers, wrists, elbows, shoulders and right hip). The subject was provided with sufficient time to swim a few warm up laps to get accustomed to swimming with the taped LED light strings.

The subject performed a total of three trials of 3 specified swimming protocols.

The three protocols consisted of the following:

Protocol One (Conventional Stroke): The subject, while swimming the Breaststroke, was required to use their regular technique, at an effort that corresponded to the pace they would complete a 100-yard race sprint. In all except a single case, the subject's "conventional stroke" consisted of the initiation of the kick coinciding with the beginning stage of the insweep, called the "early insweep."

Protocol Two (Late Kick): The subject, while swimming the Breaststroke, was required to time the initial draw-up of the kick to coincide with the period during which the hands were in the final stage of the second phase of the Breaststroke pull pattern (the insweep), called the "late insweep."

Protocol Three (Delayed Late Kick): The subject, while swimming the Breaststroke, was required to time the initial draw-up of the kick to coincide with the period during which the hands were beginning the "recovery" phase, i.e. hands moving forwards.

Subjects were asked to repeat a trial if they did not meet the criteria for a given condition, with a maximum of three trials per condition, and were given time to rest between trials in order to eliminate fatigue as a confounding variable during the second and third trials.

The video data was then uploaded to the digitizing software, where it was digitized and the footage was synchronized to produce dynamic peak velocity-time graphs to analyze the fluctuations in peak velocities. The trials were compared to each other to record the resulting differences between the peak velocity, the minimum velocity recorded during the effort, and the velocity regained as the next stroke was initiated.

Statistical Analysis of Data

Each subject's stroke was digitized and analyzed using the Motus and Templo software. The percentage drop-off in peak velocity, percentage of the velocity regained, maximum hip velocity generated by the arms, and maximum hip velocity generated by the legs were seen through the use of time-velocity graphs (Figure 2).

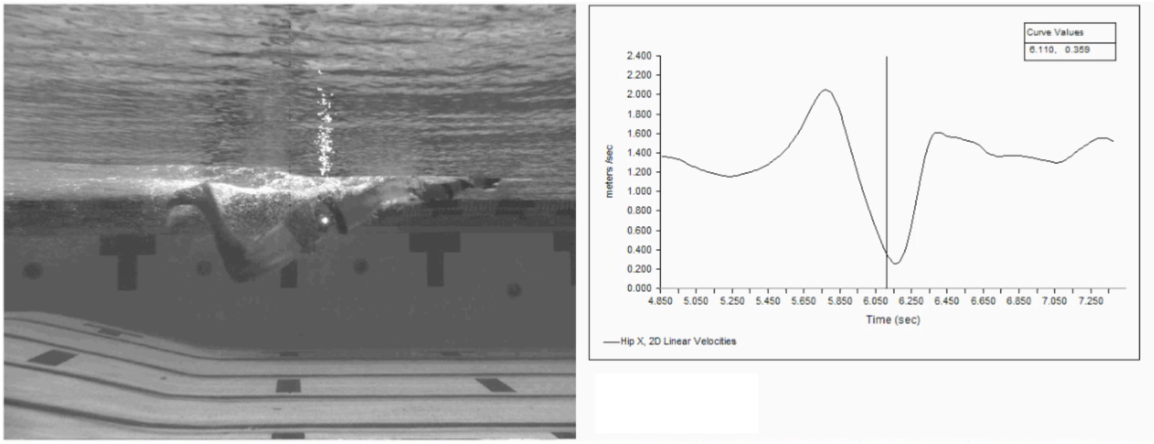

Figure 2. Time-velocity graph used to analyze velocities of the Breaststroke.

Maximum knee flexion angle and time to complete kick were measured by using Templo's angle measure function on a time-stamped video (Figure 3).

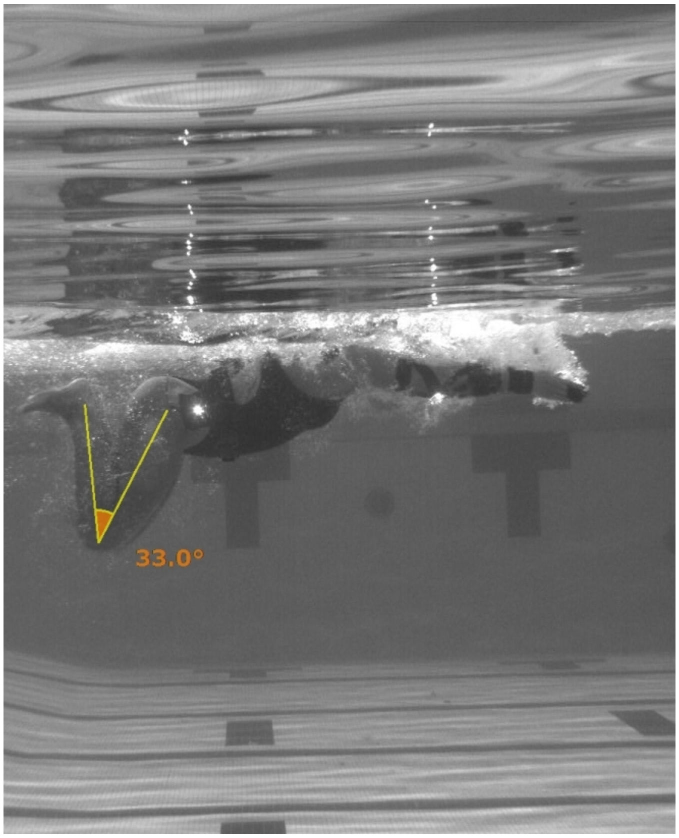

Figure 3. Maximal knee flexion angle calculated in Templo.

Due to the single-subject design of this study, each subject's own trials were analyzed against each other to note any significant difference in the timing of the Breaststroke kick on peak velocity (note difference in drop-off/regained); for example, subject 1's Protocol 1 trial, Protocol 2 trial, and Protocol 3 trial were all compared against each other, but subject 1's Protocol 1 trial was not compared against subject 2's Protocol 1 trial. For each dependent variable, all of the data variance for each subject was compared against respective data variance for the other subjects for all trials; for example, subject 1's maximal knee flexion angle for

Protocol 1 trial was compared to subject 2's maximal knee flexion angle for Protocol 1 trial. The significant difference for each protocol was determined using ANOVA repeated measures analysis with a significance level set to p=0.05 (Field 2009). Mauchly's test of sphericity was run to validate the parameters of the ANOVA repeated measures analysis with a significance level set at p=0.05 (Field 2009). Greenhouse-Geisser and Huynh-Feldt corrections were used with the Mauchly's test; Huynh-Feldt correction was used for peak hip velocity generated by the legs, and Greenhouse-Geisser correction was used for all other dependent variables (Field 2009).

Results

Subjects in this study were n=9 NCAA Division I swimmers. Anthropometric data collected for these subjects included: age, height, weight, body mass index, and wingspan. The data is displayed in table 1.

Table 1. Anthropometric measurements.

Variable	Mean	SD
Age, years	20.67	1.32
Height, in.	70.34	3.81
Weight, lb.	158.34	16.96
Body mass index, kg/m^2	22.49	1.56
Wingspan, in.	71.11	5.73

SD=Standard Deviation

Following the statistical analysis of their trials, the means, standard deviations, and 95% confidence intervals for all variables were calculated and are reported in table 2. Also calculated in table 2 are pairwise comparisons of data to demonstrate significance between the three different kick techniques for each dependent variable.

Table 2. Comparison of Breaststroke Biomechanics with Different Kick Techniques.

	C100				DU1				DU2			
			p- value				p- value				p- value	
Measure	Mean ± SD	CI	DU1	DU2	Mean ± SD	CI	C100	DU2	Mean ±SD	CI	C100	DU1
% VDO	91.2 ± 4.9	91.3 ± 3.8	0.02	0.01	86.8 ± 5.0	86.8 ± 3.8	0.02	0.03	82.5 ± 5.2	82.5 ± 4.0	0.01	0.03
%VR	91.1 ± 11.8	91.1 ± 9.1	0.02	0.01	96.3 ± 11.6	96.4 ± 9.0	0.02	0.39	97.3 ± 10.2	97.3 ± 7.9	0.01	0.39
MKF, ^{0}	36.1 ± 5.1	36.1 ± 4.0	0.22	0.03	33.7 ± 6.8	33.7 ± 5.2	0.22	0.03	31.6 ± 6.1	31.6 ± 4.7	0.03	0.03
PAV, m/s	2.2 ± 0.5	2.2 ± 0.4	0.10	0.06	1.9 ± 0.3	2.0 ± 0.3	0.10	0.23	1.9 ± 0.4	1.9 ± 0.4	0.06	0.23
PLV, m/s	2.0 ± 0.4	2.0 ± 0.3	0.42	0.27	1.9 ± 0.3	1.9 ± 0.3	0.42	0.43	1.8 ± 0.4	1.8 ± 0.3	0.27	0.43
TCK, s	0.6 ± 0.1	0.7 ± 0.1	0.02	0.05	0.7 ± 0.1	0.7 ± 0.1	0.02	0.36	0.7 ± 0.1	0.7 ± 0.1	0.05	0.36

% VDO= Percentage Velocity Drop-off; %VR=Percentage of Velocity Regained; MKF=Maximum Knee Flexion Angle; PAV=Peak Hip Velocity Generated by the Arms; PLV=Peak Hip Velocity Generated by the Legs; TCK=Time to Complete Kick; C100=Conventional Stroke 100-yd sprint pace; DU1=Late Kick; DU2=Delayed Late Kick; SD=Standard Deviation; CI=Confidence Interval

Comparative Significant Differences

When comparing "Conventional Stroke" and the "Late Kick," significant differences were seen in the following parameters:

a) Time taken to complete kick.

b) Percentage of hip velocity drop-off.

c) Percentage of velocity regained.

When comparing “Conventional Stroke” and the “Delayed Late Kick,” significant differences were seen in the following parameters:

a) Maximal knee flexion angle.
b) Time taken to complete kick.
c) Percentage of hip velocity drop-off.
d) Percentage of velocity regained.

When comparing the “Late Kick” to the “Delayed Late Kick, significant differences were seen in the following parameters:

a) Maximal knee flexion angle.
b) Percentage of hip velocity drop-off.

To ensure the validity of the significance found in the ANOVA repeated measures analysis, Mauchly’s test of non-sphericity was run. Huynh-Feldt correction was used for peak hip velocity generated by the legs, and Greenhouse-Geisser correction was used for all other dependent variables. Partial eta squared was also calculated to determine how much of the change seen in each variable could be attributed to the condition alone. Changes in kick protocol account for 11-56% of the difference seen for each dependent variable. This data is shown in table 3.

Table 3. Univariate tests for dependent variables.

	Mauchly's		Greenhouse-Geisser		Huynh-Feldt	
Measure	Sig.	W	Sig.	Partial Eta Sq.	Sig.	Partial Eta Sq.
% VDO	0.05	0.435	0.01	0.558	0.01	0.558
%VR	0.28	0.695	0.01	0.516	0.00	0.516
MKF, ^{0}	0.08	0.489	0.05	0.354	0.05	0.354
PAV, m/s	0.04	0.411	0.07	0.331	0.06	0.331
PLV, m/s	0.11	0.531	0.36	0.110	0.36	0.116
TCK, s	0.06	0.447	0.04	0.379	0.04	0.379

MKF=Maximum Knee Flexion Angle; PAV=Peak Hip Velocity Generated by the Arms; PLV=Peak Hip Velocity Generated by the Legs; TCK=Time to Complete Kick; % VDO= Percentage Velocity Drop-off; %VR=Percentage of Velocity Regained

Peak hip velocity generated by the arms was the only variable found significant in the Mauchly's test of non-sphericity (p=0.04); Greenhouse-Geisser correction was used to determine significance for this variable (p=0.07). Therefore, all the significant values found in the ANOVA repeated measures analysis can be considered valid.

Discussion

The purpose of this study was to describe the kinematics of the conventional versus the late Breaststroke kick technique using selected variables to determine the efficiency of each technique. Currently, only one study exists that examines the effects of the timing of the Breaststroke kick on intra-cyclic velocity. However, this single study by van Houwelingen et al. used subjects that were of "average" competitive experience, and consequently not classified as competing at the elite levels. Their conclusions were limited to stating that "average-level swimmers are capable of adjusting their leg-arm coordination with acoustic cueing and that different timing of the kick does affect intra-cyclic velocity variation". (van Houwelingen et al., 2017) Unfortunately, this study does not specifically address leg-arm coordination, how to replicate the study, nor were they able to explain how these findings could be applied by coaches when training swimmers.

Consequently, our study is the first to have defined parameters to classify leg-arm coordination and incorporate them into a specific variation of the Breaststroke swimming technique.

In order to be designated as a “Conventional Stroke”, “Late Kick” or a “Delayed Late Kick”, the time at which the kick reached 160 degrees of flexion was matched with the phase at which the pulling action of the hands coincided with this position of the knee.

During the protocol where the subjects were required to swim using their “Conventional Stroke”, the distinguishing feature was that the initiation of knee flexion took place during the early stages of the second phase of the Breaststroke arm pull. This phase is termed the “early insweep” as compared to the “late insweep” which is the later stage and concluding portion of the propulsive phase of the Breaststroke pull (Figures 4a and 4b).

Figure 4a. Protocol 1: Close up of hand position during the early insweep.

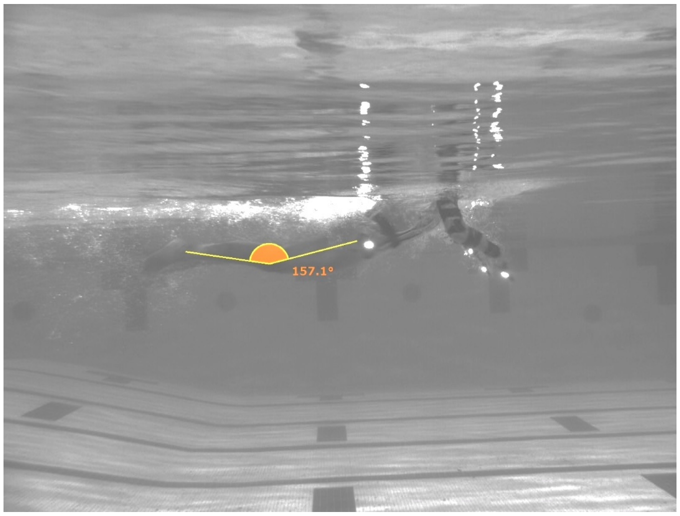

Figure 4b. Protocol 1: Coincident knee kick.

The “Late Kick” was the time the hands were completing the “ late insweep” (Figures 5a and 5b) and “Delayed Late Kick” coinciding with the position of the hands when they were starting to be thrust forwards into the recovery phase (Figures 6a and 6b).

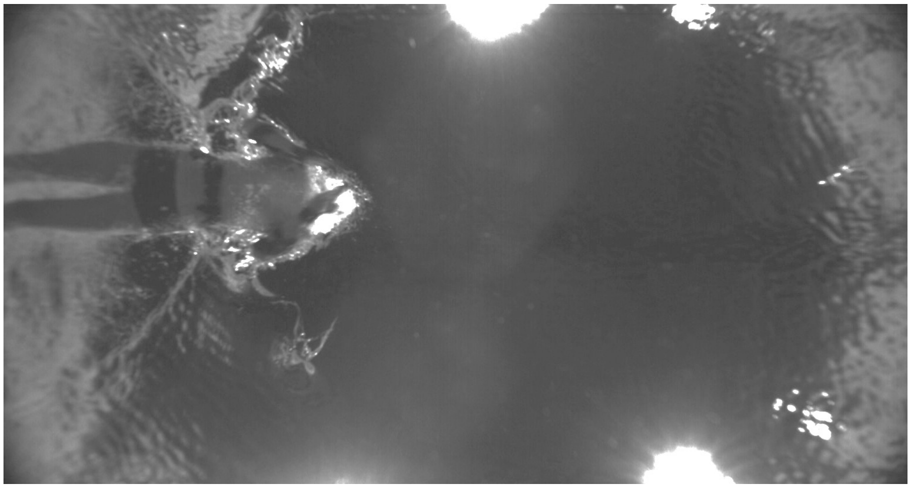

Figure 5a. Protocol 2: Close up of hand position during the late insweep.

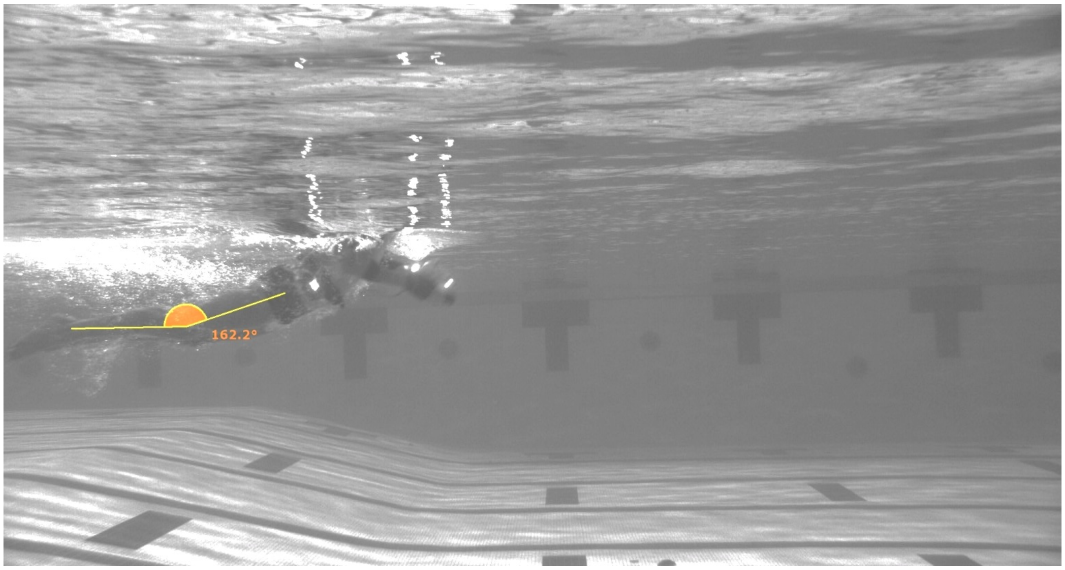

Figure 5b. Protocol 2: Coincident knee kick.

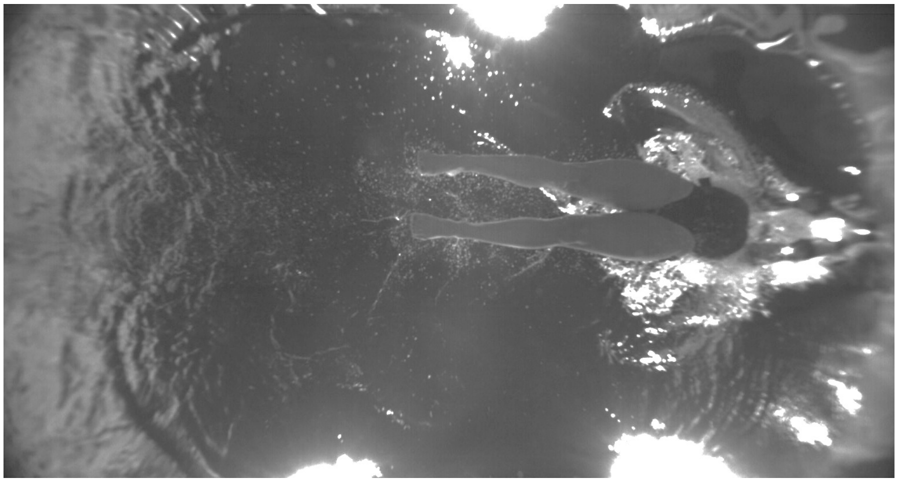

Figure 6a. Protocol 3: Close up of hand position during the early recovery.

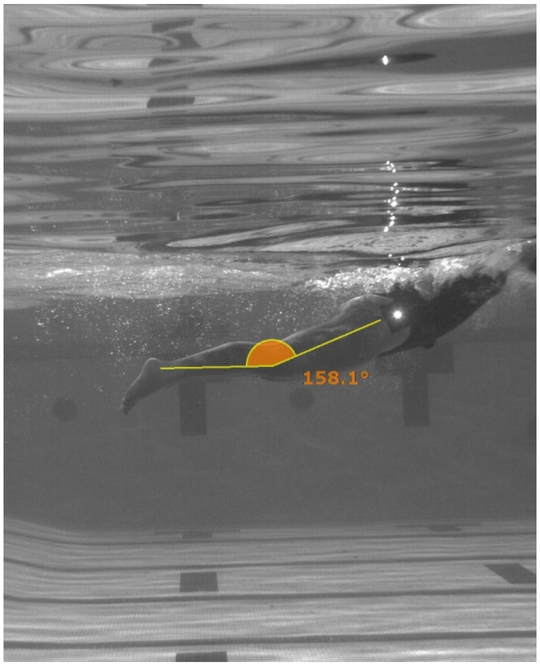

Figure 6b. Protocol 3: Coincident knee kick.

All nine subjects of this study were elite-level swimmers who were all able to perform each specified kick technique with only verbal cueing. The analysis of each subject's trials revealed that the smallest percentages of velocity drop-off were seen during the "delayed late kick" technique. That is, when the three protocols were compared, the third protocol, when the subjects waited until their hands started to be extended forwards, we observed the smallest drop-off in overall hip velocities. The second phase of "least drop-off" was the protocol designated "Late Kick", when the hands were approaching the body, during the "insweep" phase of the arm pull.

The greatest amount of velocity regained was in the late kick technique and the delayed late kick technique. This indicates a smaller velocity variation within one stroke cycle, which indicates a more efficient Breaststroke technique than the subject's normal technique. These findings are in agreement with the conclusions reached by two earlier published manuscripts (C. D. D'Acquisto LJ, 1998; van Houwelingen et al., 2017).

There were no significant differences in peak hip velocity generated by the arms or peak hip velocity generated by the legs between the subjects when using either of the three protocols. However, the fastest overall swimming velocities were achieved in the subjects' regular Breaststroke technique trials before they were asked to make adjustments to their strokes. These results were expected because all subjects tested were currently in, or recently concluded, intense training, and were instinctively swimming at their current training velocities.

Maximal knee flexion angle and time to complete kick are two variables that have not yet been studied as it relates arm-leg coordination of the Breaststroke technique and intra-cyclic velocity variations. Maximal knee flexion was significantly different between the regular Breaststroke technique and the delayed late kick technique, but not between the regular Breaststroke technique and the late kick technique. What was observed was that the subjects tended to increase the degree of knee flexion, the later they were asked to kick in their stroke. These changes may be attributed to the perception of the overall stroke cycle taking more time, thereby allocating more time to increase the amount of knee flexion. As expected, this also increased the total durations of the "Late Kick" and "Delayed Late Kick" when compared to the durations of the subjects' kick when swimming their "Conventional Stroke".

In regards to the research questions posed for this experiment, it can be concluded that there is a significant difference between hip velocities as a function of the initiation of knee flexion and hand positions during the Breaststroke pull phase. It can be concluded that there is less of a drop-off in hip velocities, and higher values for regaining hip velocities, accompanying later durations of the pull phase.

Practical Applications

The conclusions derived from this study are in agreement with the current trend in competitive sprint Breaststroke technique. Although the timing of the leg draw-up during the longest competitive distance, the 200 meters, still shows relatively early draw-up of the kick, the findings of the study shows clear differences when there is a delay before the initiation of the kick when swimming the shorter competitive distances.

This study revealed that by virtue of smaller decreases in the periods of velocity "drop-off", higher swimming velocities may be achieved when the kick is initiated during the insweep or early recovery arm phases. This study also proves that video analysis and verbal cueing are both viable feedback tools that can be used to help swimmers learn to make adjustments to their regular techniques to become more efficient in the water.

CHAPTER 1:
INTRODUCTION

Introduction

The Breaststroke can be broken down into three phases, the Kick, the Pull, and the Glide. When these three phases are completed in succession, a swimmer has completed one full cycle of the Breaststroke. The variations in the overall swimming velocity throughout one Breaststroke cycle are a good indicator of the swimmer's stroke efficiency; the more efficient a swimmer's stroke is, the better they will perform (Takagi, Sugimoto, Nishijima, & Wilson, 2004). A number of current studies have examined the coordination of the arms and the legs during the Breaststroke cycle (C. D. D'Acquisto LJ, 1998; Leblanc, Seifert, & Chollet, 2009; van Houwelingen, Roerdink, Huibers, Evers, & Beek, 2017). The earlier studies mainly focus on periods of propulsion provided by each phase and how they affect the acceleration and deceleration of the entire cycle. The most recent study by van Houwelingen et al. noted swimmers are capable of manipulating their arm-leg coordination resulting in intra-cyclic velocity variations. However, their results were inconclusive.

During the 2016 Olympics, British swimmer Adam Peaty won the men's 100-meter Breaststroke race in world-record fashion using a kick technique that performs the kick phase of the Breaststroke later than it is conventionally taught. To our knowledge, there is currently no research that examines how the timing of the initiation of the kick, when occurring during different phases of arm pull can affect the propulsion, acceleration, and consequently intra-cyclic velocity of the Breaststroke.

The lack of research regarding analysis of the timing of the Breaststroke kick is likely due the relatively new nature of this technique. However, given the surprising effect this technique has had on Adam Peaty's gold-medal, world-record performance at the 2016 Olympic games, it is clear that this technique should be investigated to determine if his performances were the result of training, or improved technique.

Kinematic analysis provides invaluable information for both swimmers and coaches; video playback allows them to immediately review a swimmer's technique and obtain feedback for making corrections, and digital analysis allows a swimmer's stroke efficiency to be formally evaluated and improved (Costa et al., 2010; C. D. D'Acquisto LJ, 1998; C. D. D'Acquisto LJ, Gehtsen GM, Wong-Tai Y, Lee G, 1988; Jaszczak, 2011; Strzała et al., 2012). The hip has been validated as the most reliable anatomical landmark to use for measuring intra-cyclic velocity and its changes within a stroke; the frame-by-frame analysis that can be utilized in accompaniment with the recorded intra-cyclic velocity fluctuations allows researchers to pinpoint which aspects of the technique are contributing to the fluctuations in order to make improvements (Costa et al., 2010; C. D. D'Acquisto LJ, 1998; C. D. D'Acquisto LJ, Gehtsen GM, Wong-Tai Y, Lee G, 1988; Jaszczak, 2011; Strzała et al., 2012; van Houwelingen et al., 2017).

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Need for the Study

Currently there are no published studies that examine the effects of the timing of the Breaststroke kick during specific pull phases on intra-cyclic velocity fluctuations. The expectation is that this research can lead to improved stroke efficiency and consequently faster swimming times.

Operational Definitions

Independent Variables Measured

- <u>Conventional Stroke:</u> The kick is timed to initiate with the early insweep of the hands
- <u>Late Kick</u>: The kick is timed to initiate with the late insweep of the hands
- <u>Delayed Late Kick:</u> The kick is timed to initiate with early arm recovery
- <u>Break in Rhythm:</u> The kick is timed to initiate with the end of the arm recovery

Dependent Variables Measured

- <u>Maximum Hip Velocity Generated by the Arms (PAV):</u> The hip velocity speed (m/s) obtained by swimmer as measured at the anatomical marker placed at the hip during peak speed of arm pull
- <u>Maximum Hip Velocity Generated by the Legs (PLV):</u> The hip velocity speed (m/s) obtained by swimmer as measured at the anatomical marker placed at the hip during peak speed of leg kick
- <u>Time to Complete Kick:</u> The time (s) elapsed from initiation of kick (knee flexion angle $160^{0} \pm 3^{0}$) to termination of kick (return after maximal knee flexion to $160^{0} \pm 3^{0}$)
- <u>Maximum Knee Flexion:</u> The angle (degrees) measure between hip-knee-ankle when the subjects' legs have reached the maximal flexion point of the kick
- <u>% Drop-off:</u> The percentage of velocity lost from maximum hip velocity generated by the arms to minimum velocity during leg deceleration
- <u>% Regained:</u> The percentage of velocity regained from minimum velocity during leg deceleration to maximum hip velocity generated by the legs compared to maximum hip velocity generated by the arms

Delimitations

1. Subjects in this study were 9 healthy swimmers (4 male and 5 female), with a primary stroke focus of either Breaststroke or Individual Medley. All subjects were members of an NCAA Division I Varsity Swim Team. This subject pool was selected to ensure similar levels of competitive experience.
2. Measuring hip velocity helped to ensure the most accurate velocity measurements were recorded during the swim trials.
3. Each subject was considered their own control; each of their trials were only compared against their current stroke technique.
4. Variables were measured against the subject's own data points; data from each subject were then compared to each other.

Limitations

1. The subjects were asked to make modifications to their normal stroke technique. Because this study required variations be made to each individual's kick mechanics, it was anticipated that these changes might affect stroke performance in a way other than the factors studied, for example, the likelihood of the subject slowing down their normal cadence so as to perform the requested variation.
2. Using a repeated-measures design introduced the possibility that the subjects might modify their technique based on the previous trials. Subjects were asked to perform one modification at a time, but each trial may have had an influence on subsequent trials.
3. The results of this study were limited to the subject population used.

CHAPTER 2:
Literature Review

Historical Development of the Breaststroke Technique

Breaststroke is one of the four competitive swim strokes; as a stroke, it has developed from its origin, as a skill used for lifestyle activities such as hunting, fishing, and military purposes, to its current competitive technique (Trendafilov, 2015). When the modern technique was first developed, swimmers performed the kicking action using what was termed the "wedge kick". The belief was that at the conclusion of the kick, when the legs approached each other in bi-lateral adduction, to push a wedge of water between their legs to achieve forward propulsion, and used an underwater hand scoop motion back to the shoulder line to create forward movement from the arm pull (Trendafilov, 2015).

Later, the kick was changed to resemble a "circular pushing motion" focusing on narrowing the gap between the feet, as this was found to produce less drag while still producing the forward propulsion (Trendafilov, 2015). When analyzing the technique, the kick and the pull can each be broken down into specific phases; other kinematic factors analyzed for the Breaststroke technique include: velocity, drag/resistance, propulsion, buoyancy, and pitch.

The Phases of the Breaststroke Pull

Researchers dispute the number of phases into which the arm pull may be broken down; Takagi, Sugimoto, Nishijima, and Wilson (2004) and Martens and Daly (2012) break the arm pull down into four phases, while Seifert and Chollet (2005) break down the arm pull into five phases. Takagi et al. (2004) breaks down the arm pull into the recovery phase, the glide phase, the outsweep phase, and the insweep phase; Martens and Daly (2012) break the arm pull down into two translational phases – the outsweep and the insweep – and two rotational phases – pronation and supination of the forearm. Seifert and Chollet (2005) break the arm pull into the five phases of arm glide, arm propulsion, elbow push, upper limb propulsion, and recovery.

In the study of Takagi et al. (2004), arm recovery was defined as the period starting at maximum elbow flexion under the breast until the arms are fully extended in front of the face; the glide starts at the end of the arm recovery and ends when the first lateral movement of the arms is observed; the outsweep starts with the first lateral arm movement and ends when the hands are first seen moving down and backwards; and the insweep is the period starting at the end of the outsweep, and ending when the hands come together for the recovery motion. In the study of Seifert and Chollet (2005), the "arm glide" is the period between full arm extension and the start of the backsweep of the hand; the arm propulsion is the phase between the beginning and the end of the backsweep of the hand; the elbow push is the time starting at the end of the backsweep of the hand and the beginning of the forward hand drive and the end of the backward insweep of the elbow push; the upper limb propulsion is the sum of the arm propulsion and elbow push phases; and the recovery phase starts with the end of the elbow push and ends with the arms in full extension, stretched out in front of the face.

There has been much debate about whether the arm pull of the Breaststroke is a pulling action or a sculling action. While Newton's Law of action/reaction can be applied to forces on land, it cannot be applied to swimming strokes because the water is not a solid object to be acted upon; however, in order to apply this form of propulsion, "propulsive drag" forces would be the dominant force.

The early school of thought on Breaststroke propulsion was that propulsion in the stroke was created from lift due to the Bernoulli effect (Maglischo, 2013a, 2013b). However, Maglischo (2013) notes that the Bernoulli Theorem requires laminar flow to produce lift, and discredits this theorem as a means of propulsion by proving that water moves over a swimmer's hands during the Breaststroke in turbulent flow instead. The three-dimensional motion of the Breaststroke arm pull, created by the curvilinear, semicircular path of the hands, the simultaneous up and down motion of the hands, and shoulder adduction cause it to instead be a form of propulsion dominated by drag rather than lift, though lift is still produced (Maglischo, 2013a, 2013b). As long as the arms and hands are moving backwards to some extent, the backward force exerted by the swimmer will accelerate their body forward (Maglischo, 2013a, 2013b). Consequently, Maglischo (2013) presents a strong argument that the arm stroke is indeed a pull. The argument is presented on the basis that the Breaststroke arm motion is a drag-dominated propulsive pull rather than a sculling motion (Maglischo, 2013a, 2013b).

When computation fluid dynamics (CFD) were used in a simulation of turbulent flow water conditions over a simulated forearm and hand to further analyze the Breaststroke arm pull, maximum propulsion was found to occur when the hands were facing directly back toward the feet, even while the hands were stroking diagonally through the water (Maglischo, 2013a, 2013b). The body was accelerating when the hands were in the diagonal-backwards point in the outsweep and deceleration of the body began when the hands started moving forward during the insweep (Maglischo, 2013a, 2013b).

Based on these findings, Maglischo (2013) had several recommendations about the best technique for the Breaststroke arm pull, including: the arms should move back in a large sideward, shoulder adducting, semicircular sweep; the propulsive phase of the insweep should terminate and the recovery should begin after the swimmer has completed about two-thirds of the recovery; and that the elbows should travel beyond the shoulders in order to lengthen the propulsive phase of the insweep.

Findings from a CFD analysis of a swimmer's arm and hand during a Breaststroke pull performed by Riewald and Bixler (2001) also supported the recommendations of Maglischo (2013). Their study found acceleration and deceleration of the hands, have a greater effect on drag than on lift, and also found that they affect the arm drag twice as much as the hand drag (Riewald S, 2001). They also concluded that maximum hand propulsive force is achieved when the palm of the hand is facing directly towards the feet, even if the pull itself is moving diagonally (Riewald S, 2001). Their recommendations for the best technique for the Breaststroke arm pull include: keeping the arms and hands accelerating as much as possible, because even a slight deceleration can result in a significant reduction of propelling force; the hand should be in a position to maximize drag during the acceleration part of the stroke; placing more focus on the arm, as it plays a larger role in propulsion than previously thought; and maximizing propulsion during the phases of the arm pull where the palms are facing towards the feet (Riewald S, 2001).

Martens and Daly (2012) note that the Breaststroke pull is responsible for the second largest velocity increase during a Breaststroke stroke (kick is responsible for largest velocity increase). They note that during the arm pull, the swimmer moves from their most hydrodynamic position, the streamlined position when their arms are stretched out in front of them at the end of the recovery phase (Costa et al., 2010; Martens & Daly, 2012) to the least hydrodynamic position, when they lift their head to breathe (Martens & Daly, 2012). Contrary to Maglischo (2013), they consider the Breaststroke pull as producing more of a sculling motion, and posit that the insweep sculling is more propulsive than the outsweep sculling (Costa et al., 2010).

When specifically examining the motion of the hands, they note that the optimal hand position for creating maximum propulsion is having the fingers closed and the thumb fully abducted, and using a cupped hand with straight fingers is better than naturally bent fingers (Costa et al., 2010). Their other key findings regarded swimmers who perform the Breaststroke with an undulating motion, rather than swimming flat Breaststroke. They report that undulating Breaststroke swimmers benefit more from a longer hand path than flat Breaststroke swimmers and that during the first part of the arm pull they also accelerate more (Costa et al., 2010).

Propulsive Kick Phases of the Breaststroke

Researchers dispute the number of phases in the leg kick; while Takagi et al. (2004) separate the leg kick into three phases, Seifert and Chollet (2005) analyze the Breaststroke kick by breaking it down into five phases. The three phases described by Takagi et al. (2004) include the sweep, the lift and glide, and the recovery phases; the five phases described by Seifert and Chollet (2005) include these phases, but have added two more phases: leg propulsion, leg insweep, leg glide, recovery part one, and recovery part two. Leg propulsion is the phase of the kick that begins with the first backward movement of the feet and ends when the legs have reached full extension (Seifert & Chollet, 2005). Leg insweep refers to the phase of that starts when the legs reach full extension and ends when the legs are joined together(Seifert & Chollet, 2005). Leg glide is the phase of the kick that begins when the legs are joined together and ends when the legs begin to be flexed forward (Seifert & Chollet, 2005). Leg recovery refers to the phase(s) that begins with the end of leg glide and ends with the termination of the forward movement of the feet (Seifert & Chollet, 2005).

These phases combine to create one Breaststroke kick, which causes the largest velocity increase during a Breaststroke stroke (Martens & Daly, 2012). The first large increase in velocity is due the extension of the legs with the feet pronated – the leg propulsion phase (Martens & Daly, 2012; Seifert & Chollet, 2005). A second, slightly smaller increase in velocity is seen as the leg propulsion phase ends and the legs finish the circular kicking motion during the leg insweep, during which the feet should supinate to continue to provide forward propulsion for the swimmer (Martens & Daly, 2012; Seifert & Chollet, 2005). During this moment, as the legs finish extending, the swimmer's maximum moment of inertia during the stroke occurs; however, the minimum moment of inertia occurs quickly after when the legs become fully flexed at the end of the recovery phase (Cohen, Cleary, Harrison, Mason, & Pease, 2014).

The Glide Phase in the Breaststroke

As has already been noted, the arm and leg phases each have their own respective glide phases; however, there is a overall "glide phase" that is included as part of the Breaststroke stroke (Seifert & Chollet). The glide phase is a period of deceleration in the stroke. In order for the swimmer to minimize their deceleration, they attempt to maintain a streamlined position during the glide phase of the stroke (Seifert & Chollet) since the streamline position is the most hydrodynamic body position (Costa et al., 2010).

A swimmer may vary the amount of time they spend in the glide phase of the stroke depending on the distance of the race; 200m swimmers tend to optimize their stroke economy by lengthening the glide phase and decreasing the stroke rate (Strzała et al., 2012). In a study by Takagi et al. (2004), it was noted that the non-propulsive phase of the stoke, the glide, may be more important for higher performance than the propulsive phase. They stated that a characteristic of better performing swimmers was the lesser reduction in velocity during the non-propulsive phase – essentially, a lower drop-off between intra-cyclic peak velocities (Takagi et al., 2004).

Head Positions in the Breaststroke

A study by Stallman, Major, Hemmer, and Haavaag (2010) analyzed the Breaststroke from a survival perspective, and in their study it was noted that swimming the stroke with the head up and out of the water displaces the center of gravity of the body further backwards from the center of buoyancy of the swimmer, which leads to an increase in the amount of frontal resistance the swimmer encounters. Swimming Breaststroke with the head out of the water not only increased the resistance, but consequently caused greater muscular exertion and earlier fatigue of the swimmers; swimming with a normal breathing pattern, where the head is submerged for part of the stroke, was found to be the optimal way to breathe during the Breaststroke (Stallman, Major, Hemmer, & Haavaag, 2010). However, current literature is sparse in regard to the optimal time taken to lift the head to breathe during the Breaststroke.

Arm-Leg Coordination in the Breaststroke

A swimmer's success in the water can largely be attributed to their ability to effectively apply propulsive forces in the water (C. D. D'Acquisto LJ, 1998). Though the arm pull and the leg kick can each be broken down into their own phases, they are performed simultaneously during the Breaststroke stroke and the stroke itself has its own phases (C. D. D'Acquisto LJ, 1998; Leblanc et al., 2009). Leblanc, Seifert, and Chollet (2009) break the Breaststroke down into the following phases: simultaneous recovery of the arms and legs; the leg kick; the glide; and the arm pull and insweep.

The leg kick provides propulsion, however, the leg recovery produces a deceleration in velocity; during this time the arm pull also provides propulsion (Leblanc et al., 2009). Similar findings are supported by the study of D'Acquisto and Costill (1998), who break the Breaststroke down into four phases – two phases of acceleration and two phases of deceleration. The first phase of acceleration is the leg kick, followed by the first phase of deceleration composed of the completion of the arm recovery and the outsweep of the hands, which is then followed by the second phase of acceleration when the arms provide propulsive actions through their insweep motion, and ending with a second phase of deceleration when the legs recover and the hips and knees become flexed (C. D. D'Acquisto LJ, 1998).

The velocity variations found within one Breaststroke stroke cycle can be a good indicator of the efficiency of the swimmer's technique (C. D. D'Acquisto LJ, 1998; van Houwelingen et al., 2017); stroke index can also be used to evaluate the efficiency of a swimmer's stroke (Barbosa, Marinho, Costa, & Silva, 2011; Seifert & Chollet, 2005). Seifert and Chollet's (2005) study examining the stroke index for Breaststroke also confirms that the recovery and glide phases of the Breaststroke stroke are phases of deceleration, and that the time the body is spent in a streamlined position is the period when active drag is limited and velocity is best maintained. According to a study performed by Jaszczak (2011), asymmetrical leg movements can result in an increase in asymmetrical hand movement as well. Poor body alignment can lead a swimmer to experience increased drag forces, which may hinder their ability to swim faster (Strzała et al., 2012); in contrast, proper body alignment while swimming helps the swimmer to reduce the drag forces they experience and increase their speed (Sanders et al., 2015).

A study performed by Sanders et al. examined asymmetries of an elite-level Breaststroke swimmer in order to identify the causes of misalignments in the stroke (2015). They found that different levels of torque produces misalignments during various parts of the stroke; positive torque during the outsweep, the recovery of the upper limbs, and during the kick and negative torque during the insweep and prior to the kick were all identified causes (Sanders et al., 2015).

Kinematic Factors Relating to the Timing of the Breaststroke

There are several kinematic factors that are to be examined when evaluating optimal efficient technique of the Breaststroke. Since the main goal of competitive swimmer is to increase speed through efficient stroke mechanics, velocity is the best variable to use for assessing stroke performance (Barbosa et al., 2011). Velocity can further be broken down into two components: stroke rate, referring to how quickly a full cycle of the Breaststroke stroke is performed, and stroke length, which refers to the distance covered by a full cycle of the Breaststroke stroke (Barbosa et al., 2011). Stroke rate and stroke length work together in an inverse relationship; a swimmer with high stroke rate will have a lower stroke length, and vice versa (Barbosa et al., 2011).

A higher stroke rate coupled with a lower stroke length is found to produce greater speed, and is the technique highly favored by Breaststrokers in the shorter distance races (50 meter and 100 meter events); a lower stroke rate with a higher stroke length is used to optimize the economy of the glide phase and is the technique more favored by swimmers in longer distance Breaststroke races (200 meter events) (Strzała et al., 2012). In Breaststroke, the timing between the movements of the arms and the legs is also a major concern (Barbosa et al., 2011). It has been suggested that higher swim velocities may be achieved by reducing the time spent during the glide phase in the stroke, and by increasing the partial duration, and the propulsive force during the final actions of the underwater curvilinear trajectories of the arms (Barbosa et al., 2011).

Horizontal velocity and intra-cyclic variations have been deemed the most important biomechanical variables in competitive swimming. Horizontal velocities of the Breaststroke at the hip in the longitudinal plane of motion are the most commonly measured (Barbosa et al., 2011; van Houwelingen et al., 2017). In Breaststroke, the horizontal velocity is characterized by a bi-modal profile, with one peak relating to the actions of the arms and the other peak relating to the actions of the legs (Barbosa et al., 2011). A low intra-cyclic variation of the horizontal velocity leads to greater swim technique efficiency for the swimmer (Barbosa et al., 2011).

The other key variable that is examined is propulsion. The contributions of lift and drag forces to overall propulsion are still widely debated (Barbosa et al., 2011). In the study of Barbosa et al. (2011) they note that there is a large amount of propulsion generated by the arms, and that different positions of finger spreading can change the amount of propulsion that is produced. Drag is defined as “an external force that acts in the swimmer’s body parallel but in the opposite direction of his movement direction” (Barbosa et al., 2011). The resistive forces that drag produces can be influenced by any one of several factors. These include: anthropometric characteristics of the swimmer; characteristics of the equipment used by the swimmer; physical characteristics of the swimming field; and the swimmer’s technique (Barbosa et al., 2011). Barbosa et al. (2011) also noted that it is important to look at active drag, and not just passive drag, because the variables pertaining to drag forces can change when the subject in the water is actively moving, in contrast to being towed through the water.

Velocity-Video Analysis Validation

Many studies use the velocity-video system and view it as a reliable way to analyze the stroke mechanics of the Breaststroke, and often some type of markers are placed on the swimmer at specific anatomical landmarks before the trial begins, and these markers are used to help digitize and analyze the film after it has been recorded (Costa et al., 2010; C. D. D'Acquisto LJ, 1998; C. D. D'Acquisto LJ, Gehtsen GM, Wong-Tai Y, Lee G, 1988; Jaszczak, 2011; Strzała et al., 2012).

A study performed by D’Acquisto, Costill, Gehtsen, Wong-Tai, & Lee (1988) set out to validate a velocity-video system for use in analyzing Breaststroke economy, skill, and performance. The swimmers in their study were filmed using the velocity-video system as well as another biomechanical analysis system that had previously been validated; after using a computer program to digitize the film and analyze the stroke mechanics, a comparison of the two analyses proved the velocity-video system to be a valid system to use in the analysis of swim stroke mechanics (C. D. D'Acquisto LJ, Gehtsen GM, Wong-Tai Y, Lee G, 1988). Using the velocity-video system, the film of the swimmer was able to be divided into propulsive and non-propulsive velocity data. Distance per stroke (stroke length), the peak minimum and maximum velocities achieved within the stroke cycle, and the time spent and distance travelled per each stroke were measured (C. D. D'Acquisto LJ, Gehtsen GM, Wong-Tai Y, Lee G, 1988). This method was found to be a reliable way to determine horizontal stroke velocity, and when velocity time graphs were synchronized with the film of the swimmer’s trial, it provided a quick and reliable feedback for swimmers and their coaches (C. D. D'Acquisto LJ, Gehtsen GM, Wong-Tai Y, Lee G, 1988).

CHAPTER 3:
Methods

Study Objectives

The purpose of this study was to describe the results of a kinematic analysis of the "conventional" vs. "late" Breaststroke kick, using selected variables of these two types of kick patterns. The study was divided into two elements, each posing the following questions:

Question 1: Is there a significant difference in peak hip velocity drop-offs between the two techniques (conventional vs. late) of Breaststroke kicking?

Hypothesis 1: There will be a significant difference between the two techniques of kicking – there will be less of a drop-off in peak hip velocity for the subjects who utilize the late kick technique.

Question 2: Is there a significant difference in the percentage of velocity regained during the propulsive phase of the kick related to the magnitude of velocity percentage drop-off during kick deceleration?

Hypothesis 2: There will be a significant difference in the percentage of velocity regained during the propulsive phase of the kick related to the magnitude of velocity percentage drop-off – the smaller the percentage velocity drop-off, the greater the percentage of velocity regained will be.

Research Design

This study utilized a single-subject design by examining the effects on peak velocity during the Breaststroke with three different trials of executing the kick during different phases of the stroke. The independent variable was the timing of the kick (conventional, late, or delayed late) and the dependent variables were maximal knee flexion angle, peak arm velocity, peak leg velocity, time to complete kick, percentage of velocity drop-off, and percentage of velocity regained.

Participants

Subjects were recruited from an NCAA Division I swimming team (4 males & 5 females). n=9 subjects (G*Power a priori analysis: ANOVA repeated measures, within factors; effect size f= 0.5; p=0.05; power= 0.8; number of groups= 1; number of measurements= 3; correlation among repeated measures= 0.5; non-sphericity correction = 1)

Inclusionary criteria: Breaststroke must be one of their primary competitive events; they must have reached NCAA Division I levels of competitive experience.
Exclusionary criteria: Non-experienced competitive swimmers; injury that prevents swimmer from swimming with normal technique; Breaststroke is not a primary race event for the swimmer.

Performance Site

This study was performed at the Duke Kahanamoku Aquatic Complex, on the campus of the University of Hawaiʻi – Mānoa.

Instruments

- Three high-speed digital cameras (Baumer Model HXG with CMOS sensors), installed in custom housings (The Sexton Company, Salem, Oregon).

- All 3 housings were attached to custom-designed mounting frames and positioned so as to provide the three required fields of view (Figure 1).

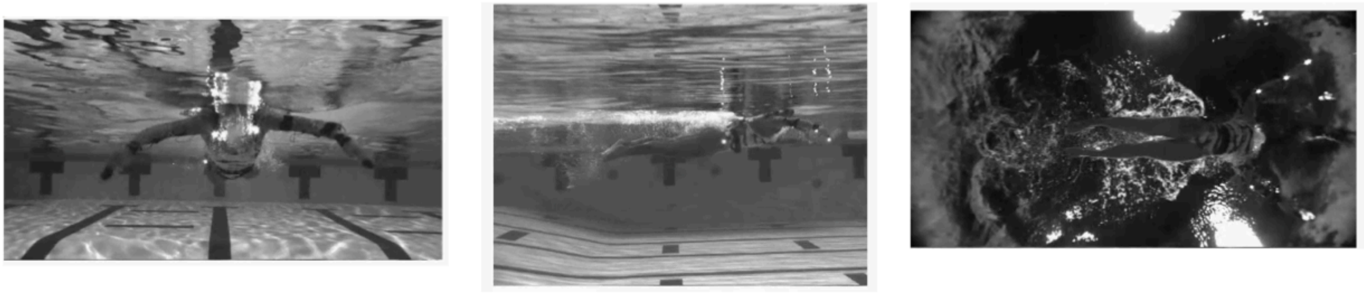

Figure 1. Synchronized frames of the three camera angles used to film swimming trials.

- Camera 1 was used for recording the frontal, or head-on view, of the subject's progress and was mounted on a vertically oriented frame. The camera was positioned at a depth of 0.48 meters (1.57 feet).

- Camera 2 was mounted on a horizontal platform that rested on the bottom of the pool at a depth of 2.13 meters (7 feet). The camera was aligned vertically, i.e. pointing upwards to the surface and provided a transverse view of the subject's progress.

- Camera 3 was mounted on a laterally positioned frame that was bolted to the concrete deck of the pool. The camera was positioned at a depth of 0.48 meters (1.57 feet), similar to the depth of Camera 1. The lateral orientation of Camera 3 provided the data for the progress of the subject in the longitudinal plane of motion.

- The distance the subject was required to cover in each trial varied between 11.89 and 13.71 meters (39 to 45 feet). This distance was determined by placing the camera that was used for recording the frontal, or head-on view of the subject at a distance of 13.71 meters (45 feet) yards from the side of the pool from which the subject was required to push-off at the start of each trial. Subjects were instructed to swim directly towards this camera, approaching it as close as possible without colliding with the camera.

- The cameras were controlled via dual 9.14 meter-long (30 feet) Gigabit (GigE) Ethernet cables connected to a desktop computer located on the pool deck. Each camera had two cables - one cable was assigned to camera control and another cable was used for frame synchronization. Unlike the limitations relating to maximum functional lengths inherent when using Firewire cabling, GigE cabling does not have a length restriction, which allowed for optimum placement of the underwater cameras in the pool.

- Rotational joint segments were identified using a custom-designed string of light emitting diodes (LED's), housed in waterproof housings. The LED's were duct taped to the body and powered by a battery pack attached to a belt worn by the subject at the waist.

- Templo (Contemplas, Kempten, Germany) motion capture software was used for capturing and recording the video data.

- A second software package, Motus, (Contemplas, Kempten, Germany), was used for digitizing, data analysis, and generating "reports". This software included a "Multi 2-D" (M2-D) feature, which enabled multiple cameras to be synchronized. Each sequence was digitized using a combination of auto-tracking and manual modes.

- IBM Statistical Package for the Social Sciences (SPSS) version 23 was used to run statistical analysis.

Kinematic Data Collection Procedures

After obtaining approval for the study from the University of Hawaiʻi at Mānoa University Institutional Review Board for the Study of Human Subjects, Breaststroke subjects were recruited from the University of Hawaiʻi at Mānoa Intercollegiate Swimming Team. Subjects reported to the pool at a scheduled time, and signed a consent form. Prior to videotaping, each subject was shown a previously digitized swim trial so as to familiarize them with the outcome of the videotaping and resulting "report. " Following the recording of each subject's anthropometric data, the LED lights were taped on to specific anatomic landmarks (bilateral fingers, wrists, elbows, shoulders and right hip). The subject was provided with sufficient time to swim a few warm up laps to get accustomed to swimming with the taped LED light strings.

The subject performed a total of three trials of 3 specified swimming protocols.

The three protocols consisted of the following:

Protocol One (Conventional Stroke): The subject, while swimming the Breaststroke, was required to use their regular technique, at an effort that corresponded to the pace they would complete a 100-yard race sprint. In all except a single case, the subject's "conventional stroke" consisted of the initiation of the kick coinciding with the beginning stage of the insweep, called the "early insweep."

Protocol Two (Late Kick): The subject, while swimming the Breaststroke, was required to time the initial draw-up of the kick to coincide with the period during which the hands were in the final stage of the second phase of the Breaststroke pull pattern (the insweep), called the "late insweep."

Protocol Three (Delayed Late Kick): The subject, while swimming the Breaststroke, was required to time the initial draw-up of the kick to coincide with the period during which the hands were beginning the "recovery" phase, i.e. hands moving forwards.

Subjects were asked to repeat a trial if they did not meet the criteria for a given condition, with a maximum of three trials per condition, and were given time to rest between trials in order to eliminate fatigue as a confounding variable during the second and third trials.

The video data was then uploaded to the digitizing software, where it was digitized and the footage was synchronized to produce dynamic peak velocity-time graphs to analyze the fluctuations in peak velocities. The trials were compared to each other to record the resulting differences between the peak velocity, the minimum velocity recorded during the effort, and the velocity regained as the next stroke was initiated.

Statistical Analysis of Data

Each subject's stroke was digitized and analyzed using the Motus and Templo software. The percentage drop-off in peak velocity, percentage of the velocity regained, maximum hip velocity generated by the arms, and maximum hip velocity generated by the legs were seen through the use of time-velocity graphs (Figure 2).

Maximum knee flexion angle and time to complete kick were measured by using Templo's angle measure function on a time-stamped video (Figure 3).

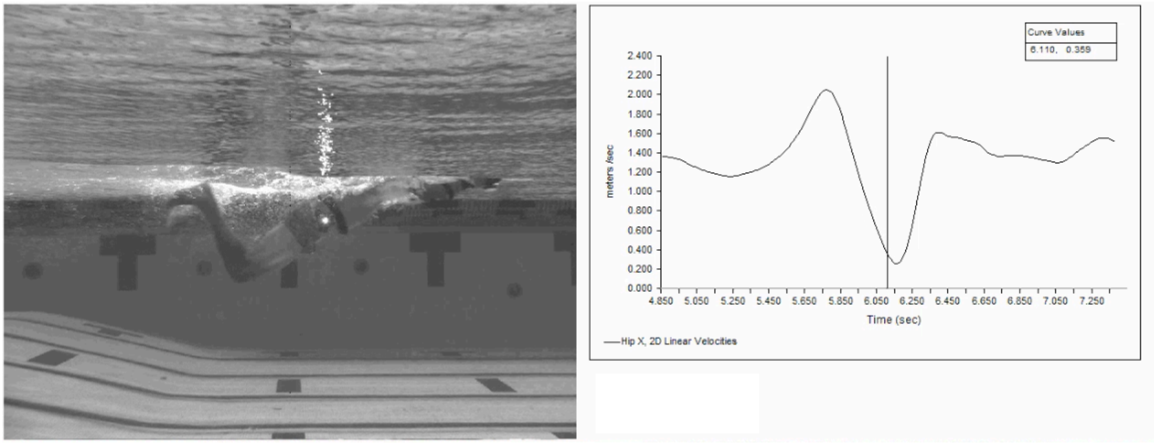

Figure 2. Time-velocity graph used to analyze velocities of the Breaststroke.

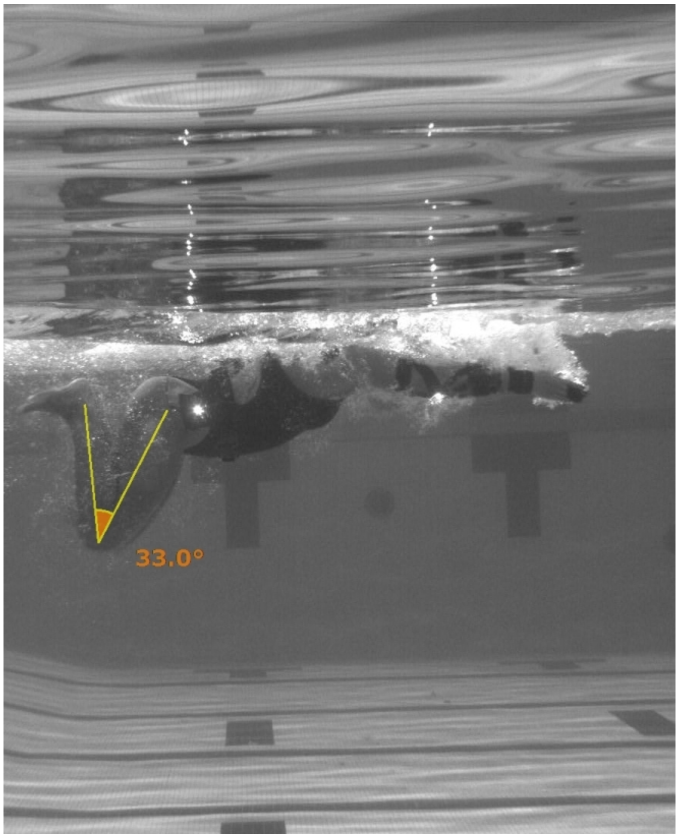

Figure 3. Maximal knee flexion angle calculated in Templo.

Due to the single-subject design of this study, each subject's own trials were analyzed against each other to note any significant difference in the timing of the Breaststroke kick on peak velocity (note difference in drop-off/regained); for example, subject 1's Protocol 1 trial, Protocol 2 trial, and Protocol 3 trial were all compared against each other, but subject 1's Protocol 1 trial was not compared against subject 2's Protocol 1 trial. For each dependent variable, all of the data variance for each subject was compared against respective data variance for the other subjects for all trials; for example, subject 1's maximal knee flexion angle for Protocol 1 trial was compared to subject 2's maximal knee flexion angle for Protocol 1 trial. The significant difference for each protocol was determined using ANOVA repeated measures analysis with a significance level set to p=0.05 (Field 2009). Mauchly's test of sphericity was run to validate the parameters of the ANOVA repeated measures analysis with a significance level set at p=0.05 (Field 2009). Greenhouse-Geisser and Huynh-Feldt corrections were used with the Mauchly's test; Huynh-Feldt correction was used for peak hip velocity generated by the legs, and Greenhouse-Geisser correction was used for all other dependent variables (Field 2009).

Results

Subjects in this study were n=9 NCAA Division I swimmers. Anthropometric data collected for these subjects included: age, height, weight, body mass index, and wingspan. The data is displayed in table 1.

Table 1. Anthropometric measurements.

Variable	Mean	SD
Age, years	20.67	1.32
Height, in.	70.34	3.81
Weight, lb.	158.34	16.96
Body mass index, kg/m^2	22.49	1.56
Wingspan, in.	71.11	5.73

SD=Standard Deviation

Following the statistical analysis of their trials, the means, standard deviations, and 95% confidence intervals for all variables were calculated and are reported in table 2. Also calculated in table 2 are pairwise comparisons of data to demonstrate significance between the three different kick techniques for each dependent variable.

Table 2. Comparison of Breaststroke Biomechanics with Different Kick Techniques.

	C100				DU1				DU2			
			p- value				p- value				p- value	
Measure	Mean ± SD	CI	DU1	DU2	Mean ± SD	CI	C100	DU2	Mean ±SD	CI	C100	DU1
% VDO	91.2 ± 4.9	91.3 ± 3.8	0.02	0.01	86.8 ± 5.0	86.8 ± 3.8	0.02	0.03	82.5 ± 5.2	82.5 ± 4.0	0.01	0.03
%VR	91.1 ± 11.8	91.1 ± 9.1	0.02	0.01	96.3 ± 11.6	96.4 ± 9.0	0.02	0.39	97.3 ± 10.2	97.3 ± 7.9	0.01	0.39
MKF, ^{0}	36.1 ± 5.1	36.1 ± 4.0	0.22	0.03	33.7 ± 6.8	33.7 ± 5.2	0.22	0.03	31.6 ± 6.1	31.6 ± 4.7	0.03	0.03
PAV, m/s	2.2 ± 0.5	2.2 ± 0.4	0.10	0.06	1.9 ± 0.3	2.0 ± 0.3	0.10	0.23	1.9 ± 0.4	1.9 ± 0.4	0.06	0.23
PLV, m/s	2.0 ± 0.4	2.0 ± 0.3	0.42	0.27	1.9 ± 0.3	1.9 ± 0.3	0.42	0.43	1.8 ± 0.4	1.8 ± 0.3	0.27	0.43
TCK, s	0.6 ± 0.1	0.7 ± 0.1	0.02	0.05	0.7 ± 0.1	0.7 ± 0.1	0.02	0.36	0.7 ± 0.1	0.7 ± 0.1	0.05	0.36

% VDO= Percentage Velocity Drop-off; %VR=Percentage of Velocity Regained; MKF=Maximum Knee Flexion Angle; PAV=Peak Hip Velocity Generated by the Arms; PLV=Peak Hip Velocity Generated by the Legs; TCK=Time to Complete Kick; C100=Conventional Stroke 100-yd sprint pace; DU1=Late Kick; DU2=Delayed Late Kick; SD=Standard Deviation; CI=Confidence Interval

Comparative Significant Differences

When comparing "Conventional Stroke" and the "Late Kick," significant differences were seen in the following parameters:

a) Time taken to complete kick.
b) Percentage of hip velocity drop-off.
c) Percentage of velocity regained.

When comparing "Conventional Stroke" and the "Delayed Late Kick," significant differences were seen in the following parameters:

a) Maximal knee flexion angle.
b) Time taken to complete kick.
c) Percentage of hip velocity drop-off.
d) Percentage of velocity regained.

When comparing the "Late Kick" to the "Delayed Late Kick, significant differences were seen in the following parameters:

a) Maximal knee flexion angle.
b) Percentage of hip velocity drop-off.

To ensure the validity of the significance found in the ANOVA repeated measures analysis, Mauchly's test of non-sphericity was run. Huynh-Feldt correction was used for peak hip velocity generated by the legs, and Greenhouse-Geisser correction was used for all other dependent variables. Partial eta squared was also calculated to determine how much of the change seen in each variable could be attributed to the condition alone. Changes in kick protocol account for 11-56% of the difference seen for each dependent variable. This data is shown in table 3.

Table 3. Univariate tests for dependent variables.

	Mauchly's		Greenhouse-Geisser		Huynh-Feldt	
Measure	Sig.	W	Sig.	Partial Eta Sq.	Sig.	Partial Eta Sq.
% VDO	0.05	0.435	0.01	0.558	0.01	0.558
%VR	0.28	0.695	0.01	0.516	0.00	0.516
MKF, ^{0}	0.08	0.489	0.05	0.354	0.05	0.354
PAV, m/s	0.04	0.411	0.07	0.331	0.06	0.331
PLV, m/s	0.11	0.531	0.36	0.110	0.36	0.116
TCK, s	0.06	0.447	0.04	0.379	0.04	0.379

MKF=Maximum Knee Flexion Angle; PAV=Peak Hip Velocity Generated by the Arms; PLV=Peak Hip Velocity Generated by the Legs; TCK=Time to Complete Kick; % VDO= Percentage Velocity Drop-off; %VR=Percentage of Velocity Regained

Peak hip velocity generated by the arms was the only variable found significant in the Mauchly's test of non-sphericity (p=0.04); Greenhouse-Geisser correction was used to determine significance for this variable (p=0.07). Therefore, all the significant values found in the ANOVA repeated measures analysis can be considered valid.

Discussion

The purpose of this study was to describe the kinematics of the conventional versus the late Breaststroke kick technique using selected variables to determine the efficiency of each technique. Currently, only one study exists that examines the effects of the timing of the Breaststroke kick on intra-cyclic velocity. However, this single study by van Houwelingen et al. used subjects that were of "average" competitive experience, and consequently not classified as competing at the elite levels. Their conclusions were limited to stating that "average-level swimmers are capable of adjusting their leg-arm coordination with acoustic cueing and that different timing of the kick does affect intra-cyclic velocity variation". (van Houwelingen et al., 2017) Unfortunately, this study does not specifically address leg-arm coordination, how to replicate the study, nor were they able to explain how these findings could be applied by coaches when training swimmers.

Consequently, our study is the first to have defined parameters to classify leg-arm coordination and incorporate them into a specific variation of the Breaststroke swimming technique.

In order to be designated as a "Conventional Stroke", "Late Kick" or a "Delayed Late Kick", the time at which the kick reached 160 degrees of flexion was matched with the phase at which the pulling action of the hands coincided with this position of the knee.

During the protocol where the subjects were required to swim using their "Conventional Stroke", the distinguishing feature was that the initiation of knee flexion took place during the early stages of the second phase of the Breaststroke arm pull. This phase is termed the "early insweep" as compared to the "late insweep" which is the later stage and concluding portion of the propulsive phase of the Breaststroke pull (Figures 4a and 4b).

Figure 4a. Protocol 1: Close up of hand position during the early insweep.

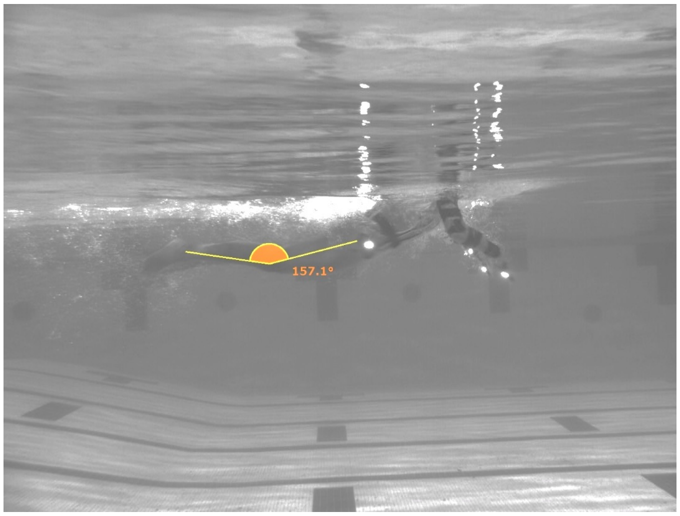

Figure 4b. Protocol 1: Coincident knee kick.

The “Late Kick” was the time the hands were completing the “ late insweep” (Figures 5a and 5b) and “Delayed Late Kick” coinciding with the position of the hands when they were starting to be thrust forwards into the recovery phase (Figures 6a and 6b).

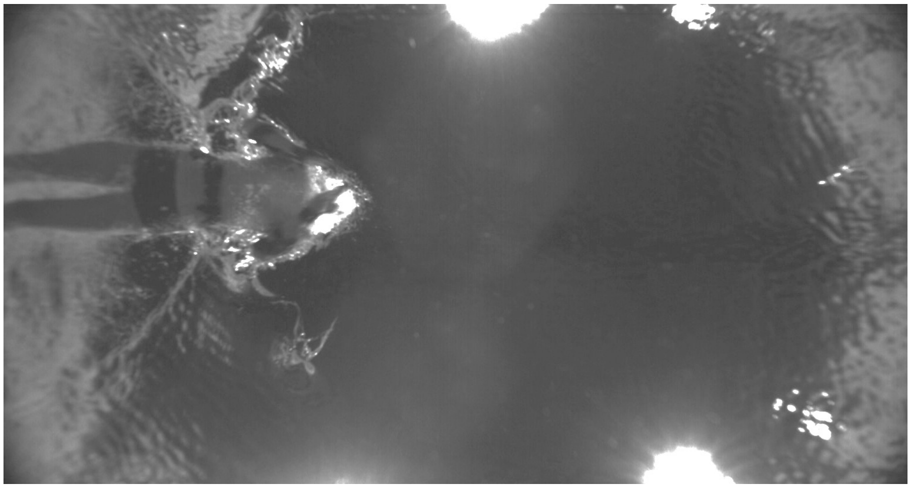

Figure 5a. Protocol 2: Close up of hand position during the late insweep.

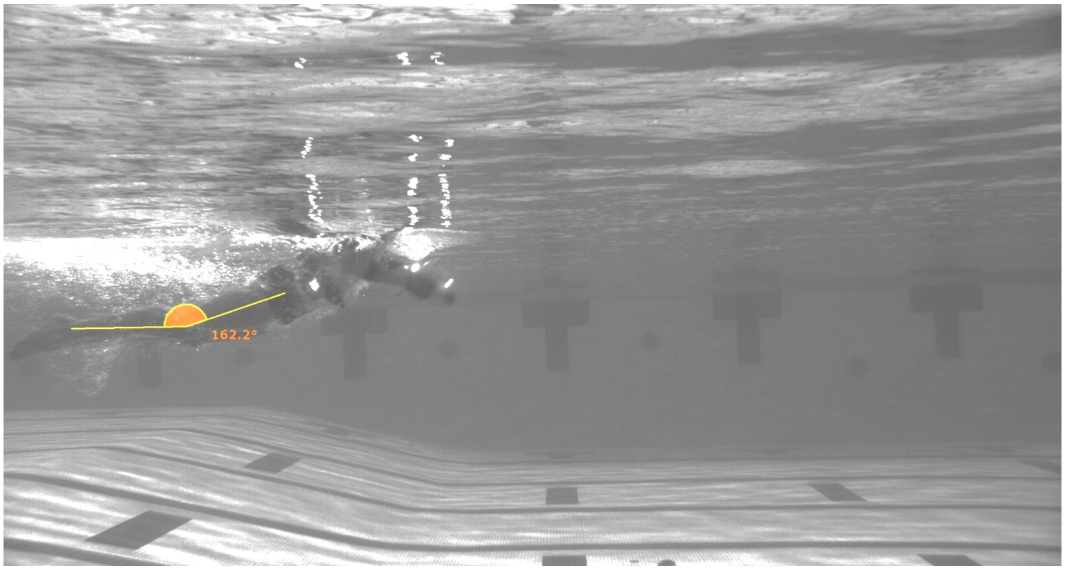

Figure 5b. Protocol 2: Coincident knee kick.

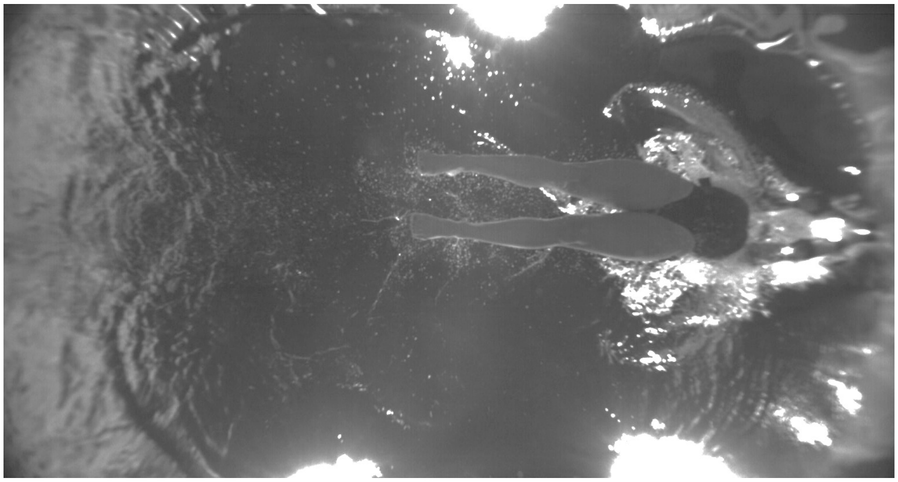

Figure 6a. Protocol 3: Close up of hand position during the early recovery.

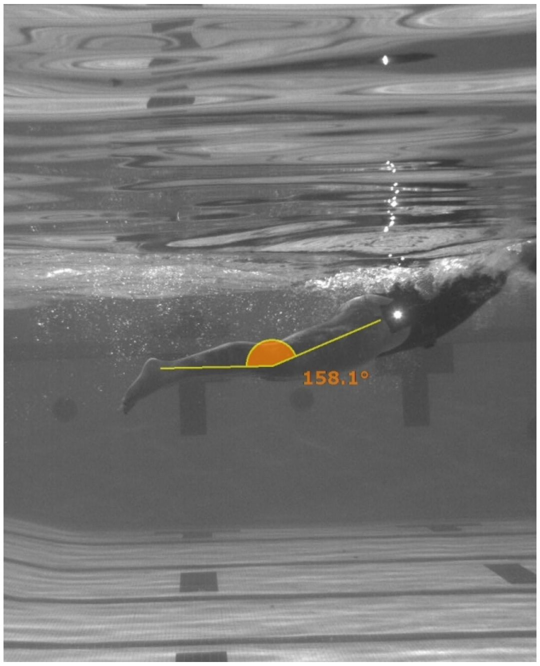

Figure 6b. Protocol 3: Coincident knee kick.

All nine subjects of this study were elite-level swimmers who were all able to perform each specified kick technique with only verbal cueing. The analysis of each subject's trials revealed that the smallest percentages of velocity drop-off were seen during the "delayed late kick" technique. That is, when the three protocols were compared, the third protocol, when the subjects waited until their hands started to be extended forwards, we observed the smallest drop-off in overall hip velocities. The second phase of "least drop-off" was the protocol designated "Late Kick", when the hands were approaching the body, during the "insweep" phase of the arm pull.

The greatest amount of velocity regained was in the late kick technique and the delayed late kick technique. This indicates a smaller velocity variation within one stroke cycle, which indicates a more efficient Breaststroke technique than the subject's normal technique. These findings are in agreement with the conclusions reached by two earlier published manuscripts (C. D. D'Acquisto LJ, 1998; van Houwelingen et al., 2017).

There were no significant differences in peak hip velocity generated by the arms or peak hip velocity generated by the legs between the subjects when using either of the three protocols. However, the fastest overall swimming velocities were achieved in the subjects' regular Breaststroke technique trials before they were asked to make adjustments to their strokes. These results were expected because all subjects tested were currently in, or recently concluded, intense training, and were instinctively swimming at their current training velocities.

Maximal knee flexion angle and time to complete kick are two variables that have not yet been studied as it relates arm-leg coordination of the Breaststroke technique and intra-cyclic velocity variations. Maximal knee flexion was significantly different between the regular Breaststroke technique and the delayed late kick technique, but not between the regular Breaststroke technique and the late kick technique. What was observed was that the subjects tended to increase the degree of knee flexion, the later they were asked to kick in their stroke. These changes may be attributed to the perception of the overall stroke cycle taking more time, thereby allocating more time to increase the amount of knee flexion. As expected, this also increased the total durations of the "Late Kick" and "Delayed Late Kick" when compared to the durations of the subjects' kick when swimming their "Conventional Stroke".

In regards to the research questions posed for this experiment, it can be concluded that there is a significant difference between hip velocities as a function of the initiation of knee flexion and hand positions during the Breaststroke pull phase. It can be concluded that there is less of a drop-off in hip velocities, and higher values for regaining hip velocities, accompanying later durations of the pull phase.

Practical Applications

The conclusions derived from this study are in agreement with the current trend in competitive sprint Breaststroke technique. Although the timing of the leg draw-up during the longest competitive distance, the 200 meters, still shows relatively early draw-up of the kick, the findings of the study shows clear differences when there is a delay before the initiation of the kick when swimming the shorter competitive distances.

This study revealed that by virtue of smaller decreases in the periods of velocity “drop-off”, higher swimming velocities may be achieved when the kick is initiated during the insweep or early recovery arm phases. This study also proves that video analysis and verbal cueing are both viable feedback tools that can be used to help swimmers learn to make adjustments to their regular techniques to become more efficient in the water.

Appendix A: Consent Form

University of Hawaiʻi
Consent to Participate in Research Project:

Kinematic Analysis of Peak Velocities in the Breaststroke as a Function of the Timing of the Kick

My name is Susan Ward. I am a graduate student at the University of Hawaiʻi at Mānoa in the Department of Kinesiology. 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 in the kick for Breaststroke swimming. I am asking you to participate because of your participation as a Breaststroke specialist on the U.H. swim team between the 2017 and 2018 intercollegiate swimming seasons.

Activities and Time Commitment: I am asking for your permission to use video filming to record and analyze your Breaststroke technique. This research will require a one-session commitment of approximately 1.5-2 hours. You will be one of nine people who will be filmed and analyzed for this study. I will measure your wingspan before the start of the session, as well as height and weight (if not known). LED lights will then be fixed to the fingers, wrist, elbows, shoulders, and hips with duct tape to hold the markers in place in the water. You will then be filmed while swimming 12 Breaststroke trials with different technique variations. Filmed will be analyzed to measure changes of velocity within one stroke cycle to determine stroke efficiency. You will be contacted to review your individual results upon the completion of their analysis if you wish to review them. Your film may be used, as video or as still photos taken from the video, to present the results of this research study.

Potential Risks/Benefits: Potential risks of the study include all the risks involved with swimming – fatigue, cramping, and drowning. To ensure the participants' safety, they will be allowed as much time as they need to rest between trials, there will be a lifeguard present during filming, and filming will be performed in the shallow end of the pool, where the participants will be able to touch the bottom of the pool while having their heads out of the water. Another potential risk is feeling discomfort from having the LED lights taped on – as the lights are taped on, the swimmers will be asked to perform the motions of their normal technique to help the researcher affix the lights in a manner that will allow the swimmer to perform the trials with comfortable swimming technique. The swimmers will be allowed to swim a few trials as warm-up trials to become accustomed to the feel of swimming with the lights on their body. If the lights become uncomfortable while performing the trials, the researcher will be available to re-tape the lights in a more comfortable position before continuing on with the study. Potential benefits of the study include the possibility of definitively discovering at which point in the Breaststroke cycle a swimmer should begin their kick in order to perform with the greatest amount of stroke efficiency – which in turn would lead to faster performances. Though this study offers no direct benefit to the swimmer, indirectly they may also be able to increase the efficiency of their stroke.

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 Hawaiʻi 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 Hawaiʻi 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 film (video/still picture) when the research is published you can designate that on this form. If you do not consent to have your film used, you will not be included in the study. I will 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:
Susan Ward, Principal Investigator at: [susan37@hawaii.edu, 910-585-1098]

An Independent Institutional Review Board (IRB) has approved this voluntary consent form and study. You may contact the UH Human Studies Program at (808) 956-5007 or uhirb@hawaii.edu to discuss problems, concerns and questions; obtain information; or offer input with an informed individual who is unaffiliated with the specific research protocol. Please visit https://www.hawaii.edu/researchcompliance/information-research-participants for more information on your rights as a research participant.

Signature:
I have read and understand the information provided to me about being in the research project, *Kinematic Analysis of Peak Velocities in the Breaststroke as a Function of the Timing of the Kick*
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 film when publishing research. (No names will be disclosed).
Signature: ____________________________________

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

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