THE EFFECT OF BREATHING ON HIP ROLL ASYMMETRY IN COMPETITIVE FRONT CRAWL SWIMMING

A Thesis
Submitted to the Faculty of Graduate Studies and Research
In Partial Fulfillment of the Requirements
For the Degree of
Master of Science
In
Kinesiology & Health Studies
University of Regina
By
Michael Barber
Regina, Saskatchewan
December, 2013

Copyright 2013: M. Barber
Michael Vincent Barber, candidate for the degree of Master of Science in Kinesiology & Health Studies, has presented a thesis titled, *The Effect of Breathing on Hip Roll Asymmetry in Competitive Front Crawl Swimming*, in an oral examination held on December 2, 2013. The following committee members have found the thesis acceptable in form and content, and that the candidate demonstrated satisfactory knowledge of the subject material.

External Examiner: *Dr. Joel L. Lanovaz, University of Saskatchewan*

Supervisor: *Dr. John Barden, Faculty of Kinesiology & Health Studies*

Committee Member: *Dr. David Gerhard, Department of Computer Science*

Committee Member: *Dr. Paul Bruno, Faculty of Kinesiology & Health Studies*

Chair of Defense: *Dr. Dena McMartin, Faculty of Engineering & Applied Science*

*via SKYPE*
Abstract

Front crawl swimming is a cyclic activity in which swimmers alternate arm and leg movements to create propulsive forces while the body rotates about its longitudinal axis. It has been suggested that breathing increases body rotation and potentially disrupts the symmetry of the stroke. This study quantified the effect of breathing on hip roll angle using a body-fixed (lower back) tri-axial accelerometer. Twenty (13 male, 7 female) provincial and national level swimmers performed four 100m front crawl trials at 70% of their best 100m time with 2 minutes recovery between trials. Four breathing conditions were tested: 1) unilateral preferred side, 2) unilateral non-preferred side, 3) bilateral and 4) non-breathing (snorkel). Peak unilateral hip roll angles, total hip roll angle and a hip roll asymmetry index were calculated for each condition. The results showed that total hip roll angle was significantly greater (p < 0.05) in the preferred (114.8°), non-preferred (118.8°) and bilateral (117.2°) breathing conditions compared to the non-breathing condition (108.3°). Further, subjects rolled significantly more (p < 0.05) to the preferred side than the non-preferred side when not breathing in the unilateral conditions (54.3° vs. 51.7°) and significantly more (p < 0.05) to the non-preferred side in the non-breathing condition (56.2° vs. 52.1°). Finally, the unilateral breathing conditions demonstrated significantly greater hip roll asymmetry than the non-breathing and bilateral conditions, whilst the bilateral breathing condition demonstrated significantly less hip roll asymmetry than the non-breathing condition. The findings demonstrate that breathing patterns affect hip roll asymmetry when performing front crawl at a submaximal speed.
The results also support the use of an accelerometer to measure hip roll angles in front crawl swimming.
Acknowledgement

This dissertation would not have been possible without the guidance and support of numerous individuals and organizations.

Special thanks to my academic supervisor,

Dr. John Barden.

Thank you to my committee members,

Dr. Paul Bruno and Dr. David Gerhard

Thank you to the funding organizations,

Faculty of Graduate Studies and Research (FGSR)

Swim Saskatchewan

University of Regina Athletics

I would also like to thank,

University of Regina Swimming Team

Regina Optimist Dolphins Swimming Club

My family

My fellow graduate students Craig, Christian, Dylan, Simon, Mads, Markus and Khaled

My Cougar Track and Field team mates and coaches
Table of Contents

Abstract ............................................................................................................................................... ii
Acknowledgements .......................................................................................................................... iv
Table of Contents ............................................................................................................................ v
List of Tables ..................................................................................................................................... vii
List of Figures ................................................................................................................................... viii

CHAPTER 1: INTRODUCTION ........................................................................................................... 1

CHAPTER 2. LITERATURE REVIEW ................................................................................................. 5

2.1 Swimming Mechanics .................................................................................................................. 5
  2.11 Stroke Characteristics ................................................................................................................. 5
  2.12 Drag Forces .................................................................................................................................. 8

2.2 Body Roll ...................................................................................................................................... 9
  2.21 Methods of determining body roll ............................................................................................... 11
  2.22 Effect of speed on body roll ......................................................................................................... 13
  2.23 Effect of drag on body roll ........................................................................................................... 14
  2.24 Effect of breathing on body roll .................................................................................................. 15

2.3 Bilateral Asymmetry .................................................................................................................... 17
  2.31 Bilateral asymmetry in front crawl .............................................................................................. 18
  2.32 Effect of breathing on bilateral asymmetry ............................................................................... 20

2.4 Accelerometry ............................................................................................................................. 21
  2.41 Stroke cycle characteristics ...................................................................................................... 24
  2.42 Stroke parameters ....................................................................................................................... 25
  2.43 Body roll angle ............................................................................................................................ 27

CHAPTER 3. METHODS ...................................................................................................................... 31

  3.1 Participants .................................................................................................................................. 31
  3.2 Data collection device ................................................................................................................... 32
  3.3 Experimental protocol .................................................................................................................. 33
  3.4 Data processing ............................................................................................................................ 35
  3.5 Statistical analysis ......................................................................................................................... 36

CHAPTER 4. RESULTS ......................................................................................................................... 38

CHAPTER 5. DISCUSSION ...................................................................................................................... 50

  5.1 Use of an accelerometer ............................................................................................................... 50
  5.2 Total hip roll angle ....................................................................................................................... 52
5.3 Peak hip roll angle ........................................................................................................54
5.4 Bilateral asymmetry .....................................................................................................57
5.5 Practical applications and future direction .................................................................59

CHAPTER 6. CONCLUSION ..................................................................................................61

CHAPTER 7. REFERENCES .................................................................................................62

Appendix. .............................................................................................................................

A – Consent Form and Information Sheet .........................................................................68
B - Accelerometer vs. video validation of roll angle calculation .......................................72
List of tables

Table 1. Test procedure........................................................................................................37

Table 2. Statistical analysis ................................................................................................37

Table 3. Subject anthropometric and time trial data .........................................................40

Table 4. Mean trial time by condition and ANOVA..........................................................41

Table 5. Peak hip roll angle by condition and length.......................................................46
List of Figures

Figure 1. Front crawl stroke phases .................................................................6
Figure 2. Wrist accelerations of the three axes from one front crawl stroke ..........25
Figure 3. Axis alignment for a back mounted accelerometer ...........................28
Figure 4. Roll angle for upper and lower back measured using accelerometry ......30
Figure 5. Representative continuous hip roll angle for one length of a non-breathing trial for a single subject .................................................................38
Figure 6. Representative continuous hip roll angle for one 100m bilateral breathing trial for a single subject .................................................................39
Figure 7. Mean total hip roll angle for each breathing condition trial. ..................43
Figure 8. Mean peak hip roll angle versus side and condition............................45
Figure 9. Results of t-tests comparing mean non-breathing peak hip roll angles according to side and condition. Error bars indicate ±1 standard deviation ..........47
Figure 10. Aymmetry index (ASI) according to condition .................................49
1. INTRODUCTION

Coaches are continually striving to improve the performance of their athletes. In swimming, improved performance occurs because of improved training methods and/or technical improvements in a swimmer’s stroke mechanics. Research plays an important role in understanding movement and provides the foundation for coaches to implement evidence-based training programs and changes in stroke mechanics. The swimming pool presents a unique and challenging environment for performance analysis. The evolution of technology has allowed swimming biomechanics research to progress in recent years. Underwater video-camera systems have provided footage of swimmers from multiple angles for performance analysis. Three-dimensional camera systems have also allowed biomechanical modelling of swim stroke characteristics. However, video analysis has some limitations. It can only provide information for approximately 1-2 stroke cycles per trial due to the necessity of calibrating a small recording zone. Another limitation is the time intensive process of digitization and data processing required to extract useful data. A recent development in swimming biomechanics is the use of body sensors such as accelerometers and real-time feedback systems. The advantage of using an accelerometer is that it can record continuous data for the entire length of the pool and can continue to do this for multiple lengths. This provides information about inter-cycle and inter-length stroke variation without interrupting the natural rhythm of the stroke, which may occur when a swimmer is aware of a recording zone.
Front crawl swimming is cyclic in nature, and as a swimmer alternates between left and right hand entries, the trunk produces an angular motion about the longitudinal axis. This motion is referred to as body roll (specifically, the body roll of the trunk). Body roll is an integral part of a swimmer’s technique in that it facilitates the breathing action, reduces drag by helping a swimmer maintain a streamlined position, increases the reach of the hand to increase stroke length and may decrease the risk of a shoulder injury. Given that the trunk does not rotate as a single rigid segment, the body roll of the trunk can be measured separately at either the hip or the shoulders. When analyzed independently it has been shown that swimmers have greater body roll at the shoulders than at the hips (Psycharakis & Sanders, 2008).

Currently, there is a lack of knowledge with respect to the factors that affect body roll. This deficiency has been exacerbated by studies that have used a variety of different methodologies to examine body roll, including cameras placed above and below the water, two and three-dimensional multiple camera systems and more recently, body-fixed sensors. However, it is not clear which of these methods should be considered to be the “gold standard”, and other methodological shortcomings include limited sample sizes with no inferential statistics, retrospective analyses of race footage and participants who represent a large range of abilities and speeds.

Recent studies have shown that velocity and breathing are important factors affecting the degree of body roll during front crawl. These studies have shown that as velocity increases, body roll decreases (Yanai, 2003; Castro, Vilas-Boas & Guimaraes, 2005; Psycharakis & Sanders, 2008) and that body roll is greater when breathing than when not breathing (Beekman & Hay, 1988; Payton, Bartlett, Baltzopolous & Coombs,
A study by Psycharakis and McCabe (2011) also suggested that whilst swimmers roll their shoulders and hips significantly more to the breathing side when breathing than when not breathing, the total body roll angle (combined peak body roll angle for the breathing and non-breathing side) was not significantly different between breathing and non-breathing conditions. The authors suggested that a compensatory strategy exists on non-breathing stroke cycles to maintain a similar total body roll angle to the breathing cycles.

With respect to swimming and other cyclic locomotor activities such as walking, running and cycling, one might assume that the movement patterns of the limbs would be symmetric. However, research has shown that a degree of bilateral asymmetry is present in walking (step asymmetry) as well as in the propulsive forces of running and cycling. Evidence has suggested that the dominant leg provides propulsion whilst the non-dominant leg supports the propulsion (Sadeghi, Allard, Prince & Labelle, 2000; Carpes et al., 2011). In front crawl, a unilateral breathing pattern is likely to be associated with an asymmetric body roll, in that the swimmer will typically rotate more to the breathing side than the non-breathing side. In theory, a bilateral breathing pattern should prevent body roll asymmetry; however, no previous studies have quantified the degree of body roll angle for bilateral and unilateral breathing conditions.

Therefore, the purpose of this study was to investigate the effect of breathing on body roll angle (specifically hip roll) in competitive front crawl swimmers. More specifically, two research questions were addressed. First, how does the degree of hip roll angle differ between the following conditions: 1) breathing to the preferred side every two strokes (note: two strokes = one stroke cycle), 2) breathing to the non-
preferred side every two strokes, 3) breathing bilaterally every three strokes and 4) a non-breathing trial using a snorkel. The second research question was to what degree is hip roll asymmetry dependent on the breathing pattern of the swimmer (i.e., breathing condition)?

It was hypothesized that the degree of hip roll angle would not be equal for the preferred breathing vs. the non-preferred breathing condition, such that the degree of hip roll angle would be greater to the preferred breathing side in both unilateral breathing conditions. Furthermore, it was hypothesized that the degree of hip roll angle in the non-breathing and bilateral breathing conditions would be symmetric, whilst the unilateral breathing conditions would be asymmetric, such that the hip roll angle would be greater to the preferred breathing side.
2. LITERATURE REVIEW

2.1 Swimming mechanics

2.11 Stroke characteristics

Front crawl swimming, also known as freestyle, is a cyclic locomotor activity. The stroke cycle is generally broken down into four phases; entry and catch, pull, push and recovery (Maglischo, 2003). The entry and catch phase involves the entry of the hand into the water to full extension of the arm. The catch involves the wrist flexing downwards and the palm rotating outwards to “catch” the water in order to begin the propulsive pull phase. The catch phase has been categorized as both propulsive (Barden, Kell & Kobsar, 2011) and non-propulsive (Maglischo, 2003) in nature. The pull phase is the major propulsive phase of the stroke and can be broken down into two separate sub-phases. The downsweep involves the arm pulling downwards and outwards to the deepest point of the stroke. The insweep begins as the hand is accelerated inwards, upwards and backwards towards the midline of the body. The pull phase ends as the arm passes under the midline of the body at the deepest point of the stroke and the push phase begins. The push phase, also known as the upsweep, involves the outward and backward “push” of the hand towards the water surface. The recovery phase involves the hand leaving the water and returning over the head to enter the water at close to full extension for the next stroke cycle (McMaster & Troup, 2001). The same phases are mirrored in an opposing fashion by the contralateral arm to create the cyclic motion of the stroke.
The speed of a swimmer’s motion (i.e. velocity) is the product of the stroke length (or distance per stroke) and the stroke rate. Stroke length, as is the case with stride length in gait, is defined as the distance covered from right hand (or left) entry to the subsequent right hand entry in a single stroke cycle. Stroke rate is the number of strokes taken per minute. In swimming research, a swimmer’s velocity is generally measured from a distance of 15 metres after push off from the wall and 5 metres before the turn into the wall (Smith, Norris & Hogg, 2002). The reason for this is that stroke characteristics can vary up to 15 metres out from the wall due to rules allowing swimmers to be submerged up to 10 metres after pushing off the wall. Likewise, at a 5 metre distance from the wall, stroke characteristics change as the swimmer prepares to initiate the turn (Smith et al., 2002). Therefore, stroke rate is measured directly based on the time taken to complete one or two stroke cycles in the mid-pool recording zone, whereas stroke length must be calculated indirectly using the formula of stroke length (m) = swimming velocity (m/s) divided by stroke rate (cycles/sec) (Toussaint, Carol, Kranenborg & Truijens, 2006)

A directly proportional relationship exists between velocity and stroke rate, such that as velocity increases, stroke rate increases. The relationship between stroke rate and stroke length is more complicated, with studies showing that an increased stroke rate may be associated with either a relatively stable or decreasing stroke length. The change in stroke parameters is linear until critical speed is reached, at which point substantial and unpredictable changes in stroke parameters occur (Barden & Kell, 2009). Stroke length has been shown to be the most important parameter related to faster swimming speeds (Pelayo, Sidney, Kherif, Chollet & Tourny, 1996; Smith et al., 2002; Toussaint et
al., 2006). Expert swimmers are able to maintain a longer stroke length as stroke rate increases, resulting in a faster velocity than less skilled swimmers (Chollet et al., 1997). For a given velocity, swimmers with a longer stroke length are more efficient. Therefore, it is important for coaches to emphasize technique efficiency and the maximization of stroke length during training.

2.12 Drag forces

Hydrodynamic drag forces affect a swimmer’s propulsion. Hydrodynamic drag force can be defined as an external fluid force that acts on the swimmer’s body parallel to but in the opposite direction of motion. Hydrodynamic drag can be broken down into two types; passive and active drag. Passive drag is the drag force that occurs due to the resistance of the swimmer’s body moving passively through the water (for e.g., the drag acting on the body if the swimmer is towed through the water). Active drag is the drag force a swimmer creates while actively moving their arms and legs to produce thrust to overcome the passive drag while swimming. The 3 types of drag resistance (or force) are form drag, wave drag and friction drag. Form drag refers to the resistance of the water as a consequence of body position. Form drag increases as the surface area of the frontal plane of the body increases. For example, a slanted body position with low hips and legs will increase the surface area of the frontal plane of the body, thereby increasing the form drag. Therefore, front crawl swimmers attempt to adopt a horizontal body position to reduce form drag. Wave drag occurs as a result of the forces associated with the turbulence of the water. Swimming creates waves at the water surface and therefore swimming underwater is faster as wave drag forces are removed. The deeper the pool, the more waves will dissipate and the wave drag will be less. The lane ropes are
designed to reduce the effect of wave drag on swimmers. Finally, friction drag is dictated by the drag coefficient, which quantifies the relative interaction between the molecules of water and the particles of the material moving through the water. In the case of competitive swimmers, this force occurs as the result of the interaction between the water, the suit, the skin and/or the hair of the swimmer. The use of full body suits in training and competition are designed to reduce the effect of friction drag (McMaster & Troup, 2001). Coaches are continually trying to improve the technique of their swimmers to overcome the effects of drag and improve performance.

2.2 Body Roll

An important component of the front crawl stroke is body roll. As the swimmer alternates between left and right hand entries, the trunk produces an angular motion around its longitudinal axis. This motion is referred to as body roll. Typically, as a swimmer’s right hand enters the water peak body roll angle is observed, such that the body is rotated counter-clockwise about the longitudinal axis with the position of the right hip lower than the left. Similarly, the torso rotates in the opposite direction (i.e., clockwise) so that the right hand can exit the water. Following the entry and catch phase, the right arm begins to pull back, creating propulsion with the body rolling back to neutral then to peak body roll on the opposite side as the left hand enters the water (Counsilman, 1968). Swimming is a cyclic motion and the rolling motion of the body is linked to the propulsive and recovery phases of the arm stroke cycle.

The importance of body roll was first discussed by Counsilman (1968), who suggested that body roll could improve stroke efficiency by decreasing the distance
travelled by the recovery arm and aligning the pulling motion of the arm underneath the centre of mass to produce greater propulsion. It has also been shown that body roll is important for facilitating the breathing action (Hay, Liu & Andrews, 1993; Psycharakis & Sanders, 2008), for increasing propulsion and decreasing drag forces (Yanai, 2003; 2004) and for reducing the risk of shoulder injury (Ciullo & Stevens, 1989; Weldon & Richardson, 2001).

The trunk of a swimmer is not rigid and therefore the degree of body roll varies at the shoulder and hips. Shoulder roll is measured by the rotation of the shoulder girdle (i.e., a line joining both shoulders in the transverse plane) about the longitudinal axis of the body. Shoulder roll has a larger range of motion than hip roll due to the increased mobility of the shoulder girdle compared to the pelvic girdle. As the arm completes the upsweep and is raised out of the water for recovery, the shoulders rotate to allow the arm to recover fully while out of the water. A larger shoulder roll will allow the arm to recover higher and be more efficient as the radius of rotation of the recovery arm is decreased (Councilman, 1968; Psycharakis & Sanders, 2010). An increased shoulder and hip roll will increase the reach of the arm entering the water and subsequently increase the stroke length. A longer arm with a larger body roll at entry will place the arm in a more efficient position and allow the arm to be pulled back in line with the shoulder, thereby reducing lateral shoulder torque and reducing the stress placed on the shoulder (Councilman, 1968). It has also been suggested that an increased shoulder roll decreases drag forces by decreasing the frontal surface area of the body in the direction of motion (Hay, Liu & Andrews, 1993).
Hip roll is measured by the rotation of the pelvic girdle about the longitudinal axis of the body. As the arm moves through the recovery phase, the ipsilateral hip rotates towards the opposite side to allow the arm to enter the water. In terms of timing, it has been shown that peak hip roll occurs slightly before peak shoulder roll and that peak hip roll angle is lower than peak shoulder roll angle as the pelvic girdle exhibits less mobility. Psycharakis and Sanders (2008) have demonstrated that hip and shoulder roll exhibit different ranges of motion and reach peak angles at different times.

2.21 Methods of determining body roll

The literature on body roll is increasing and the methods used to determine body roll are varied. Two alternate methods have been used: 1) measuring the roll of the entire body (Yanai, 2003; 2004) or the roll of the trunk as a single segment (Beekman & Hay, 1988; Liu, Hay & Andrews, 1993; Payton et al., 1999) around the longitudinal axis and 2) measuring the roll of the shoulder and hip joints separately (Cappaert, Pease & Troup, 1995; Psycharakis & Sanders, 2008, Yanai, 2003, 2004).

Studies that measured the roll of the trunk as a single segment have produced similar values. Beekman and Hay (1988) demonstrated peak trunk roll values of 55° and 54° when breathing and not breathing in a group of injury-free swimmers. Similarly, Payton et al. (1999) demonstrated peak non-breathing values of 57° and slightly higher values of 66° for the breathing condition. A limitation of these studies is that data was collected at a single swimming speed which may have not been comparable between studies. In a study of increasing intensity, Castro et al. (2006) reported total roll angle values of 108-138° when breathing and 100-129° in breath-holding trials at three
increasing velocities in triathletes, sprint swimmers and distance swimmers. Consequently, these studies demonstrate that breathing and velocity are important factors that need to be taken into consideration when determining body roll. The effect of these factors will be discussed in depth later.

When analysing video of the trunk in front crawl swimmers, it is evident that the shoulders and hips roll to varying degrees. As a result, recent studies on body roll have measured the roll of the shoulders and hips separately. Shoulder and hip roll were first measured as separate components by Cappaert et al. (1995) in a study of the finalists at the 1992 Olympic Games. In the men’s 100m freestyle, 5 elite (finalists) and 7 sub-elite (semi-finalists) swimmers were measured. It was determined that swimmers rolled their shoulders considerably more than their hips (35.4° vs. 8.3° for sub-elites and 34.4° vs. -17.8° for elites, respectively). The difference in roll angles from those observed in several of the trunk roll studies is likely a function of the data collection technique. Cappaert et al. (1995) used underwater cameras to conduct a 3D analysis of shoulder and hip roll, whereas other less sophisticated methods were used in some of the other studies. This difference in data collection methods demonstrates that data across studies can be hard to compare quantitatively. A limitation of the study by Cappaert et al. (1995) was that the effect of breathing was not controlled for as the data was collected during a competition.

In an attempt to standardize measurement procedures, a method for 3D analysis of swimming was created and validated by Psycharakis, Sanders and Mill (2005). This technique uses a 6.75m³ calibration frame with 4 underwater and 2 above water synchronized cameras. This new method provided a 3D analysis of body roll, and as a
result it became possible to determine the body roll of the trunk as two separate segments – one including the shoulder and the other including the hip. Roll angles were determined by projecting the vector of the respective right joint to left joint onto the vertical plane perpendicular to the swimming direction (Psycharakis & Sanders, 2008) and roll angle was measured relative to the vertical (or longitudinal) axis.

Psycharakis & Sanders (2008) measured shoulder and hip roll in 10 male national level swimmers at a 200m front crawl speed in non-breathing trials. Swimmers swam at their maximal 200m speed and did not breathe through the calibration zone on each 25m lap. Swimmers rolled their shoulders significantly more than their hips. A total roll angle (the total range of motion from right side to left side) of 106.6° for shoulders as compared to 50.4° for hips was observed. A similar non-breathing (105.1°) and preferred-side breathing (110.3°) total shoulder roll angle was reported by Psycharakis and McCabe (2011). Total hip roll angles were observed in preferred side breathing (43.5°) and non-breathing (39.8°) conditions which were lower than the values reported by Psycharakis & Sanders (2008). The values for shoulder roll are similar to the values reported for total body roll in studies measuring the trunk as a single segment.

2.22 Effect of speed on body roll

A major limitation of the studies on body roll is that a range of velocities has been investigated. Velocities have varied greatly; 1.13-1.96 metres/second (m/s) (Beekman & Hay, 1988), 1.26-1.96m/s (Castro et al., 2006) 1.3-1.6m/s (Yanai, 2003), 1.4-1.6m/s (Psycharakis & Sanders, 2008), 1.52m/s (Payton et al., 1999), 1.76-1.81m/s (Psycharakis & McCabe, 2011) and 1.87-2.01 m/s (Cappaert et al., 1995). Given that
stroke length and stroke frequency change as a function of swimming speed, the effect of speed on body roll is an important factor that should be considered.

Some evidence of the effect of speed on body roll has been observed by Castro et al. (2006). They demonstrated that as velocity increases, body roll decreases. Triathletes, sprinters and long distance swimmers all significantly decreased body roll as self-determined velocity increased from slow to moderate to fast. Pscharakis and Sanders (2008) also observed that faster swimmers had significantly less shoulder roll than slower swimmers in a maximal 200m front crawl trial. Similarly, Yanai (2003) observed a decrease in shoulder roll (75° to 66°) as speed increased (1.3m/s to 1.6m/s). Conversely, the findings of Cappaert et al. (1995) suggested that shoulder roll did not change as a result of speed. Pscharakis and Sanders (2008) observed that hip roll increased (44.5° to 54.7°) as velocity decreased (1.68m/s to 1.45m/s) during a 200m trial, confirming that hip roll is also affected by a change in velocity. As stated previously, the data collection measures vary and comparing body roll angles across studies is difficult, but research suggests that an inverse relationship exists between body roll angle and velocity, such that as velocity increases, body roll decreases.

2.23 Effect of drag on body roll

In aquatic environments, drag forces affect the movement characteristics and velocity of objects immersed in water. In swimming, drag forces also act upon swimmers to propel the body through the water (McMaster & Troup, 2001). Cappaert et al. (1995) hypothesised that increased body roll may increase form drag by increasing the surface area of the body and subsequently reducing velocity. The findings of this study
suggested that sub-elite swimmers rolled their hips in the opposite direction to their shoulders, whilst elite swimmers rolled their hips and shoulders in the same direction. The discontinuity of coordination in hip and shoulder roll in sub-elite swimmers may result in increased drag by increasing the surface area, thus decreasing velocity. Similarly, Yanai (2003) suggested that a larger trunk twist may result in an increase in active drag which could decrease propulsion. Yanai (2004) also suggested that faster swimmers used buoyant forces to optimize the effects of body roll more effectively than slower swimmers, in that faster swimmers were able to stay higher in the water thereby reducing drag whilst rolling their body.

2.24 Effect of breathing on body roll

In swimming, breathing is essential so that oxygen is available to fuel the movement. Breathing occurs by turning the head to inhale as the arm on the breathing side reaches the end of the underwater pull phase and the opposite hand enters the water for the catch phase. At this point the body should be maximally rolled towards the breathing side (Payton et al., 1999). The breathing action needs to be integrated into the stroke cycle without interfering with the propulsive mechanism of the stroke.

Body roll angles reported in studies that compared breathing vs. non-breathing conditions are inconsistent. Beekman and Hay (1988) demonstrated that injured swimmers rolled their trunks more when breathing (60° to 48°) whilst healthy swimmers showed no difference (54° to 55°). In contrast, Payton et al. (1999) found that healthy swimmers rolled more when breathing than not (66° to 57°). A limitation of these studies is the range of velocities tested. Beekman and Hay (1988) did not differentiate between
the range of velocities attained at a self-selected swim pace and the degree of body roll. The limited sample size (n=6) in Payton et al. (1999) produced nothing but descriptive statistics, so it is not known whether the difference in body roll angle between breathing and non-breathing conditions was significant. In more recent studies, Castro et al. (2006) demonstrated a significant difference in total body roll angles between breathing and non-breathing trials at slow, moderate and fast velocities in sprint swimmers and moderate and fast velocities in long distance swimmers. Despite the decrease in the total roll angles as velocity increased, a difference between the roll angles in breathing vs. non-breathing strokes was still present.

To further understand the degree of change in body roll whilst breathing, Psycharakis and McCabe (2011) measured shoulder and hip roll angles for the preferred breathing and non-preferred breathing sides in breathing and non-breathing conditions. When comparing breathing and non-breathing conditions, total shoulder roll (110.3° to 105.1°) and hip roll (43.6° to 39.8°) were not significantly different. Conversely, when comparing the preferred breathing to non-preferred breathing side in breathing and non-breathing trials, swimmers rolled their shoulders (59.1° to 51.9°) and hips (24.5° to 20.4°) significantly more to the preferred breathing side compared to the non-preferred side. A possible reason total shoulder and hip roll were not significantly different between breathing and non-breathing conditions may have been due to the swimmer rolling slightly more to the non-preferred side than the preferred side (shoulder 53.3°-50.4° and hip 19.5°-19.1°) in non-breathing strokes to compensate for the additional roll to the breathing side and to maintain body position. Therefore, there is evidence to suggest that a swimmer rolls more to the breathing side than the non-breathing side (i.e., there is
more roll when taking a breath than when not), but a compensation strategy may exist to maintain a similar total body roll angle between breathing and non-breathing strokes.

2.3 Bilateral asymmetry

The human body appears symmetrical when viewed in the anatomical position. When performing a cyclical task, such as front crawl, it is reasonable to assume that the arms and legs of both sides of the body contribute equally to the task. However, a number of imbalances exist in the human body which may contribute to asymmetries. Asymmetries can occur in strength, flexibility and technique which can be a result of laterality, developmental factors, injury, training and/or breathing preference (Sanders, Thow & Fairweather, 2011). Each swimmer exhibits a combination of these factors which contributes to a unique stroke profile. An asymmetric stroke in front crawl can mean that more work is done by the arms and legs of one side of the body than the other. Therefore, asymmetry can affect the ability to produce propulsive force, the efficiency of propulsive force and the drag forces acting on the body.

Asymmetry in other cyclic locomotor activities has been researched in depth particularly in the area of human gait. In human gait, stride length is typically measured as the distance from heel strike to the subsequent ipsilateral heel strike. Step length is the distance from heel strike to the subsequent contralateral heel strike. Asymmetry in gait is measured by an asymmetry index (ASI) based on the difference between left and right step lengths (or step times). From the ASI, the degree of asymmetry can be determined (Sadeghi et al., 2000). An ASI can also be applied to front crawl swimming using stroke length or stroke rate to determine the presence of an underlying stroke asymmetry.
2.31 Bilateral asymmetry in front crawl

The concept of asymmetry has been investigated in studies using the index of coordination (IdC) (Chollet, Chailes & Chatard, 2000; Sefiert, Chollet & Allard, 2005). The index of coordination measures the relative timing of the propulsive phases of the stroke and can be used to determine the degree of propulsive continuity between the different stroke phases. The duration of the four phases of the stroke; entry, pull, push and recovery, are calculated and divided into propulsive and non-propulsive phases.

According to this index, three distinct coordination patterns are seen in front crawl. The catch up coordination model demonstrates a lag time between the propulsive phases of the two arms and is represented by an IdC <0%. It is asymmetric in nature as a period of non-propulsion exists, which suggests an inefficient stroke and propulsive discontinuity (Chollet et al., 2000). The opposition coordination model consists of symmetrical coordination of the propulsive phases. In this case, IdC = 0% and this mode of coordination is efficient and void of any propulsive asymmetry. The superposition coordination model exhibits an overlap of the propulsive phases and is represented by an IdC >0%. It is asymmetric as the propulsive phase of one arm begins before the propulsive phase of the other arm is complete (Chollet et al., 2000).

Chollet et al. (2000) found that as velocity increased from an 800m pace to a 100m pace to a 50m pace, the IdC changed from a catch up to an opposition to a superposition mode in skilled swimmers. A similar change in IdC was observed by Sefiert et al. (2005) in that the IdC shifted from a catch up to a superposition mode as velocity increased from a 3000m pace to a maximal pace. As the timing of the propulsive
phases change, the relative contribution of the propulsive phases also changes. As velocity increases, the time of the propulsive phase increases relative to the non-propulsive phase (Chollet et al., 2000; Seifert et al., 2005). It is believed that this strategy is employed by swimmers to increase velocity and is a function of the stroke rate and stroke length. As velocity increases, stroke rate increases whereas stroke length either stays constant or decreases. However, in absolute terms it has also been shown that the time spent in the propulsive phase decreases disproportionately to the recovery phase when speed is increased (Barden, Kell & Kobsar, 2011). Therefore, a change in velocity affects the coordination pattern adopted by front crawl swimmers and the degree of propulsive/ non-propulsive asymmetry varies according to velocity.

The degree of bilateral asymmetry can also be determined by quantifying the spatiotemporal differences between the left and right sides. Studies of cycling and running have demonstrated an asymmetric force application (Sadeghi et al., 2000; Carpes et al., 2011), such that the dominant leg was found to produce a greater force than the non-dominant leg. Sadeghi et al. (2000) suggested that the dominant limb has primarily a propulsive function whilst the non-dominant limb functions to support this propulsion. A similar suggestion was made by Seifert et al. (2005) in that the non-dominant arm installs rhythm, whilst the dominant arm is used for propulsion. An asymmetrical pulling pattern has also been reported in a swimming simulation on a swim bench (Potts, Charlton & Smith, 2002). The dominant arm recorded a greater power output than the non-dominant arm in a maximal test and the contribution of the dominant arm increased as the swimmer fatigued. Determining the force produced by each hand in
An aquatic environment is difficult and the majority of studies in this area have used a swim bench simulator.

An asymmetric pulling pattern was also demonstrated by Barden et al. (2011) in an incremental velocity set. The duration of the power phase on the non-dominant side was greater than the dominant side at lower velocities. However, the difference between the duration of the power phase of the dominant and non-dominant sides decreased as velocity increased. Therefore, the degree of bilateral asymmetry decreased as velocity increased. A similar conclusion was made by Nikodelis, Kollias and Hatzitaki (2005) who suggested that the degree of anti-phase inter-limb coupling (synchronization of left and right arm movements) increased at faster speeds. This is consistent with studies in cycling that have demonstrated an asymmetric crank torque at lower speeds. The dominant leg was found to produce a higher crank torque than the non-dominant leg at lower speeds and the bilateral asymmetry of crank torque decreased as power increased (Carpes et al., 2011). Therefore, the degree of bilateral limb asymmetry appears to be inversely related to speed and/or intensity.

2.3.2 Effect of breathing on bilateral asymmetry

The breathing motion is an important factor in the bilateral asymmetry of front crawl. There is a natural tendency to favour one side when breathing. It has been suggested that the preferred breathing side is generally to the same side as the dominant arm (Seifert, Chehenese, Tourney-Chollet & Lemaitre, 2008). A unilateral breathing pattern (breathing to the same side each stroke) is inherently asymmetric. When taking a breath it has been suggested that a swimmer has an increased body roll to that side
(Psycharakis & Sanders, 2008), a longer stroke length, a greater stroke depth and a longer duration of the underwater phase of the non-recovery arm (Vezos et al., 2007). These limited findings suggest that bilateral asymmetry in technique may occur in part as a result of unilateral breathing.

Seifert et al. (2005) demonstrated an IdC of superposition on the preferred breathing side, and opposition for the non-breathing side using unilateral breathing. A bilateral breathing pattern resulted in a symmetrical opposition IdC for both arms. A subsequent study by Seifert et al. (2008) confirmed asymmetry on the preferred side, but also reported even larger IdC asymmetry when breathing to the non-preferred side unilaterally. When breathing occurred bilaterally or in a non-breathing condition with a snorkel, asymmetry decreased. As mentioned previously, Psycharakis and Sanders (2008) measured shoulder and hip roll separately when rolling to the left and right sides (i.e., clockwise and counter-clockwise). In non-breathing trials, subjects rolled their shoulders significantly more towards their non-preferred side than to their preferred side, with a mean of 57.1°± 4.6 compared to 49.6°±5.4. The authors suggested that the greater roll on the non-preferred side could be caused by the greater propulsion from the underwater phase of the preferred arm. This is consistent with the suggestion of Sadeghi et al. (2000) and Seifert et al. (2005) that the dominant limb is used for propulsion and the non-dominant limb is used to instill rhythm.

2.4 Accelerometry

An accelerometer is a device used to measure applied acceleration in up to three planes of motion. The mechanism used in an accelerometer is a mass-spring system. When a mass-spring system is compressed or stretched due to movement, the spring
generates a proportional restoring force. Acceleration is calculated using Hooke’s Law \( F = kx \), and Newton’s 2nd law of motion \( F = ma \). The mass and stiffness of the spring are constants meaning the acceleration of the mass element can be calculated from its displacement (Kavanagh & Menz, 2008).

Thus,

\[
\text{(2.1)}
\]

Accelerometer technology has progressed in recent years and devices are now small in size, allowing for continuous, unobtrusive and reliable measurement of human movement for long periods of time (Godfrey, Conway, Meagher & Olaighin, 2008). These advances have led to the use of accelerometers to quantify movement in cyclical activities such as walking, running, rowing, skiing and swimming (Bachlin & Troster, 2012). Previous studies have used tri-axial accelerometers placed on the wrist (Oghi, 2002), head (Pansiot, Lo & Yang, 2010), and lower and upper back (Bachlin & Troster, 2012) to measure accelerations in three planes of motion in front crawl swimming.

The aquatic environment poses a challenge for researchers as traditional video recording techniques require expensive equipment for 3D analysis. The digitization of video requires long hours and is subject to digitizing error. Another limitation of video analysis is the use of a small recording zone which only allows 1-2 stroke cycles per length to be analyzed. Using a recording zone may influence swimming performance, especially if swimmers are told to control their breathing through a section of the pool. The continuous measurement afforded by accelerometry allows researchers to analyze
multiple stroke cycles per length and gather a more complete picture of how stroke characteristics change throughout a number of lengths or an entire race. Waterproof accelerometers are a unique solution to collecting accurate data in an aquatic environment. Studies have shown that accelerometer derived data for stroke parameters can be as good as or better than data derived from video (Davey, Anderson & James 2008). Recent research has also investigated the possibility of real-time feedback from body sensors (James, Burkett & Thiel, 2011; Bachlin & Troster, 2012). The ability to receive almost instantaneous data on swimming performance would provide coaches and swimmers valuable feedback on performance during training. Coaches could then compare subsequent data to determine how coaching cues and instruction resulted in performance improvements. A body roll profile of a swimmer pre- and post-injury could also provide useful information about recovery.

A range of sampling rates has been used in validation trials of accelerometers. A sampling frequency as low as 5Hz in a back worn sensor has been shown to have 95.1% accuracy in determining stroke parameters when compared to video (Siirolta, Laurinen, Roning & Kinnunen, 2011). Other commonly used sampling frequencies that have been used are 50Hz (Pansiot et al., 2010), 100Hz (James et al., 2011), 128Hz (Oghi, 2002) and 256Hz (Bachlin & Troster, 2012). Given the low frequency content of movements associated with swimming, it can be assumed that a sampling rate between 50 and 100Hz should provide sufficient accuracy for data collection.
2.4.1 Stroke cycle characteristics

In one of the first studies that investigated the use of accelerometers in swimming, Ohgi (2002) demonstrated a relationship between the phases of the front crawl stroke cycle described by Maglischo (2003) and the acceleration profile of a sensor worn on the left wrist (see Figure 2). The entry phase begins with sharp negative x-axis acceleration due to the collision between the swimmer’s hand and the water. The entry phase ceases as the y-axis equals 0 m/s² and the downsweep phase begins. The downsweep phase is characterized by an increase in positive acceleration of the x-axis and y-axis as the hand moves outwards and downwards and ends at the peak positive x-axis. The upsweep phase begins with the hand at its deepest position and the hand moves inwards and upwards causing y-axis acceleration that is negative, then positive and x-axis acceleration that is negative. The phase ends at the minimum x-axis value, and the upsweep and recovery phases begin. This phase continues as the hand moves upwards, out of the water and returns overhead to begin the next stroke, signified by peak negative x-axis acceleration. Oghi was unable to distinguish between the upsweep and recovery phases of the stroke cycle.
2.42 Stroke parameters

In the training environment coaches rely on manual timing and stroke counts to monitor training performance. Manual data collection of lap times and stroke count requires attention from coaches and athletes which could be better invested in coaching technique development. Recent studies have investigated the use of accelerometers for recording stroke parameters such as stroke rate, stroke length and lap times. Davey et al.
(2008) developed an algorithm to extract stroke parameters from the data obtained by a single accelerometer. A similar program was developed by Bachlin and Troster (2012) to extract information from a multi-sensor system. The development of programs such as these could allow coaches to access real-time data about their swimmer’s stroke characteristics to provide feedback in both training and competition environments. The information gathered will provide athletes and coaches with an electronic training diary of training sessions and performance.

Accelerometer data can also be used to determine important events. The wall push-off involves the swimmer pushing off the wall of the pool with their legs following a tumble turn and signifies the start and finish of a length. Using an accelerometer mounted on the back at the hip, Davey et al. (2008) identified wall push-off from an X-axis peak followed by a Z-axis peak from a comparison of acceleration data and video data. This finding was confirmed by Siirolta et al. (2011) and Bachlin and Troster (2012). Lap time can easily be determined by calculating the time from push-off to the next push-off. In a study of 200m trials comparing video to manual timing and accelerometer based timing, Davey et al. (2008) demonstrated accelerometer lap times were more accurate than manual timing, with a lower spread of timing error.

Another important stroke parameter that can be measured using an accelerometer is stroke rate. To determine stroke rate, the start and end of one stroke cycle needs to be identified. Using a back mounted accelerometer, Davey et al. (2008) identified the start of a stroke (i.e., the entry of the hand) by either a maxima (right hand) or minima (left hand) on the Y-axis. The stroke count from the accelerometer was comparable to the manual stroke count in magnitude and spread of error, suggesting that the accelerometer
stroke count was as accurate as a manual stroke count. This finding was confirmed by Bachlin and Troster (2012), who also calculated time per stroke from the time stamp of each peak. From this data, the average stroke rate can be calculated by the number of strokes taken per length divided by the time for that length.

Another useful stroke parameter that can be extracted from the accelerometer data is the average velocity for each length. Average velocity is equal to the distance of the length (for e.g., 25 or 50 m) divided by the time to complete the length. Average distance per stroke can also be calculated as a product of the average time per stroke multiplied by the average velocity. However, this method results in error as a swimmer pushing off the wall does not begin to stroke until up to 10 metres into a length (Bachlin and Troster 2012).

2.43 Body roll angle

Body roll and pitch angle can also be calculated using a back mounted accelerometer. The alignment of the axes of the accelerometer has been generally consistent. The x-axis is aligned with the longitudinal axis of the body in line with the spine, the y-axis is perpendicular to the x-axis, and the z-axis is vertical with respect to the swimmer and orthogonal to the x and y-axes. The alignment system is illustrated in Figure 3. Using the aforementioned alignment system, Bachlin and Troster (2012) measured hip and shoulder roll as seen in Figure 4. Pansiot et al. (2010) also measured body roll with a sensor placed on the back of the swimmer’s head. Roll angle can be calculated by determining the ratio (tangent of the angle) of the acceleration due to gravity on the Y (pitch) and Z (yaw) axes (2.2).
In addition, a swimmer is not in a perfectly horizontal position when swimming. Therefore, the pitch angle of the body can also be calculated;

\[
\text{(2.3)}
\]

Figure 3. Axis alignment for a back mounted accelerometer. Reproduced from *Swimming performance and technique evaluation with wearable acceleration sensors*, M. Bachlin & G. Troster, *Pervasive and mobile computing*, Copyright © (2011 Elsevier Ltd.). Reprinted with permission of Elsevier Ltd.
In a comparison of a simulated and actual signal, Bachlin and Troster (2012) demonstrated that the changing pitch angle had no effect on body roll. Therefore, it would appear that the degree of pitch angle has no effect on the body roll angle calculation. This is important as a swimmer’s pitch angle can change throughout a length depending on technique, drag force and fatigue. Body roll data can be used for a number of purposes. The different strokes, breaststroke, butterfly, backstroke and front crawl, each demonstrate a unique roll angle pattern which can be identified from looking at a graph of body roll angle data (Pansiot et al., 2010). In front crawl, the entry of the hand into the water correlates with the highest body roll angle of the ipsilateral side. Therefore, in theory, the entry phase can be determined from the maximum (right hand) and minimum (left hand) body roll angle values. Subsequently, a stroke count can also be determined and the time for each stroke can be calculated. Potentially, breathing strokes can also be distinguished from non-breathing strokes by a larger angle value for the breathing side compared to subsequent non-breathing angles for the same side (Pansiot et al., 2010).
Figure 4. Roll angle for upper and lower back measured using accelerometry.

*Reproduced from Swimming performance and technique evaluation with wearable acceleration sensors, M. Bachlin & G. Troster, Pervasive and mobile computing,*

*Copyright © (2011 Elsevier Ltd.). Reprinted with permission of Elsevier Ltd*
3. METHODS

3.1 Participants

An a priori power analysis was conducted at 80% power to determine the sample size required to provide sufficient power for statistical analysis. The peak hip roll angle values from previous studies (Psycharakis & Sanders, 2008; Psycharakis & McCabe, 2011) were used as variables for the power analysis. Given a medium effect size, a random sample of twenty competitive well-trained swimmers was determined as the sample size to participate in this study. It is important to use a sample of competitive swimmers because they demonstrate a developed technique which is more consistent than recreational swimmers (Pelayo et al., 1996) and it is also an important objective that the findings of this study generalize to the competitive swimming population. The minimum criteria for inclusion were as follows. First, participants must have trained as a competitive swimmer for at least three years. This was to ensure that potential participants had enough experience, instruction and training to have developed an efficient and consistent stroke technique. Second, participants had to have achieved a minimum of a provincial championship “A” qualifying standard in a front crawl event in the previous twelve months. This criterion ensured that all participants had achieved a similar minimum standard in the front crawl stroke. McCabe, Psycharakis and Sanders (2011) found that there is no significant difference in stroke parameters between sprinters and middle distance swimmers. Therefore, the distance specialty of the participants was not used as one of the criteria in this study. Finally, participants were at least 16 years of age or older at the time of the study.
A request was made to the Head Coaches of several local swim clubs to ask if their athletes wished to participate. The coaches were given copies of the participant information sheet (Appendix B) which were subsequently given to their swimmers. Participants were identified by the Head Coaches of the Regina Optimist Dolphins and University of Regina Cougars swimming clubs. The principal investigator directly contacted swimmers who had been identified by coaches as meeting the inclusion criteria (i.e., 3 years of training, 16 years of age or older and meeting a provincial qualifying standard in at least one front crawl event). Contact was made by either phone, email or in person at a training session.

Twenty university level competitive swimmers (13 male, 7 female) ranging from 18 to 24 years old (mean: 19.3 ± 1.6 years) participated in the study. Subjects were members of the University of Regina Cougars swimming team and trained six days per week. All subjects read and completed an information sheet and consent form (Appendix A). The consent form was approved by the Behavioural Research Ethics Board at the University of Regina. Subject anthropometric data is presented in Table 3.

3.2 Data collection device

A single tri-axial accelerometer (GENEActiv, Cambridge, UK) was used in this study. The accelerometer was small in size (36 mm x 30 mm x12 mm) and lightweight (16 grams). It is capable of measuring acceleration up to ± 8g. The GENEActiv accelerometer has been shown to be valid and reliable in the measurement of acceleration in physical activity (Esliger et al., 2011). A pilot investigation determined that the accelerometer was a valid method of calculating roll angle (Appendix B). The
accelerometer was attached to an elastic waist belt and fastened around the hip of the swimmer on the back at L5/S1 vertebrae. The accelerometer axes were aligned with the body such that the y-axis was in line with the spine, the x-axis perpendicular to the y-axis, and the z-axis vertical to the x and y-axes. The accelerometer was set to sample at 100 Hz. The accelerometer was turned on and off by a start/stop button embedded in the surface. Prior to entering the pool, subjects were instructed to lie face down on the pool deck for 10 seconds. In this position zero degrees of roll (i.e. a neutral position) was parallel to the pool deck. The data from this period of time was averaged to calculate the offset due to sensor placement. Subsequently, the averaged value was subtracted or added to the calculated hip roll angles values to correct for the offset caused by sensor placement.

3.3 Experimental protocol

Participants performed a normal training warm up prior to the administration of the experimental protocol. For this protocol, the participants were asked to perform a series of four 100 m repetitions at a sub-maximal speed using front crawl. Subjects were instructed to swim at 70% of their season’s best 100m front crawl time. The data collection took place in a regulation 25m indoor pool. Prior to each trial the accelerometer was turned on by the researcher. The participants then jumped vertically to provide a reference point for the researcher at the beginning of each trial. The participants began the trial from a standing start in the pool by pushing off the wall. At the end of each length, the participants performed a regular competition tumble (flip) turn. At the end of the trial, the participants jumped vertically a second time to mark the
end of the trial. Participants were allowed a full recovery of 3 minutes between trials to negate the effects of fatigue. A video camcorder was also placed on the pool deck to record each trial so that the breathing and non-breathing stroke cycles could be determined for the bilateral breathing condition.

Each participant’s preferred breathing side was determined based on a question in the consent form, which was “When you swim freestyle (front crawl) what is your preferred breathing side?” Each of the four 100m trials involved a different breathing pattern. The breathing patterns investigated were: 1) breathing to the preferred side every two strokes, 2) breathing to the non-preferred side every two strokes, 3) breathing bilaterally every three strokes and 4) a non-breathing trial using a snorkel. A similar protocol was used by Seifert et al. (2008) with the use of a snorkel to allow continuous swimming without having to turn the head to breathe. The order of the trials was randomized for each participant. Each trial was timed using a stopwatch to ensure that the velocity remained constant between trials.

Each 100 m trial provided 4 lengths of data. Previous studies have used only one length (Payton et al., 1999; Castro et al., 2006; Seifert et al., 2008) or a maximal time trial (Psycharakis & Sanders, 2009) to measure body roll with only 1-2 stroke cycles per length. The use of more than one length allows the swimmer to acquire and maintain a rhythm in their stroke and for researchers to analyze multiple stroke cycles per length. It also provides an opportunity to examine changes between lengths within each 100 m trial. Further, a maximal time trial is subject to the effects of pacing and fatigue. Using a self-selected submaximal velocity minimizes the effect of fatigue and allows the
swimmer to swim at a pace that feels natural and comfortable and is likely to produce the most efficient and consistent stroke.

3.4 Data processing

Raw acceleration data from the accelerometer for each trial was extracted using specialized software (GeneActiv, Cambridge, UK). Raw X, Y and Z-axis accelerations for each trial were imported into Microsoft Excel for data processing. The raw X, Y and Z accelerations were processed using a low-pass digital filter set at a cutoff frequency of 4 Hz in Microsoft Excel. Hip roll angles for each trial were calculated using the filtered acceleration data and the following tangential equation (3.1):

\[ \text{Hip roll angle} = \text{filtered acceleration data} \] \hspace{0.5cm} (3.1)

The peak hip roll angle on the left and right side for each stroke were calculated. Following the calculation of peak hip roll angles for each length, the hip roll angles were designated as preferred or non-preferred and the mean peak hip roll angles for each side were determined. The mean total hip roll angle (mean peak angle for the preferred side + mean peak angle for the non-preferred side) for each length and trial were also calculated. Figures 5 and 6 show a representative number of stroke cycles per length and per trial, respectively.

The degree of bilateral asymmetry between the peak preferred and the peak non-preferred side hip angles were calculated using an asymmetry index (ASI) (3.2) adapted from one described by Carpes, Mota and Faria (2010). In this equation P is the preferred side and NP is the non-preferred side.
3.5 Statistical Analysis

A repeated measures analysis of variance (RM ANOVA) was used to statistically analyze the data. The independent variables in this study included breathing (breath vs. non-breathe), body side (preferred vs. non-preferred), length (1-4) and breathing condition (preferred side, non-preferred side, bilateral and non-breathing). The dependent variables included the mean (i.e., mean for each length) total hip roll angle, the mean peak hip roll angle for each side and the mean asymmetry as determined by the ASI.

The first RM ANOVA (one-way) used length (1\textsuperscript{st}, 2\textsuperscript{nd} 3\textsuperscript{rd} and 4\textsuperscript{th}) as the within-subject variable (i.e., the repeated measure) to examine whether hip roll angle changed within each 100 m trial. It was not expected that any significant differences would be found given that participants were instructed to swim at a constant, submaximal, self-selected speed for each of the four conditions.

Next, a set of two-way RM ANOVAs were used to investigate the effect of breathing and body side for each of the four conditions. The mean peak hip roll angle for each side was used for the analysis. Table 1 shows the test procedure and the mean peak hip roll angles (represented by a number) that were calculated for each condition. The numbers in Table 2 correspond to the numbers in Table 1 and outline the set up of the statistical analysis. The first two-way RM ANOVA compared means 1-8 in Table 2 (i.e., first two columns) for 2 conditions (unilateral and bilateral) with side and breathing as the independent variables. The second two-way RM ANOVA compared means 2, 4, 7,
8, 9 and 10 (i.e., all non-breathing means) with 3 conditions (unilateral, bilateral and snorkel) and side as the independent variables.

Table 1. Test procedure

<table>
<thead>
<tr>
<th>Breathing</th>
<th>Side</th>
<th>Preferred</th>
<th>Non-pref.</th>
<th>Bilateral</th>
<th>Snorkel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preferred</td>
<td>1</td>
<td>N/A</td>
<td>5</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Non-preferred</td>
<td>N/A</td>
<td>3</td>
<td>6</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Preferred</td>
<td>N/A</td>
<td>4</td>
<td>7</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Non-preferred</td>
<td>2</td>
<td>N/A</td>
<td>8</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Statistical analysis

<table>
<thead>
<tr>
<th>Breathing</th>
<th>Side</th>
<th>Unilateral</th>
<th>Bilateral</th>
<th>Snorkel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preferred</td>
<td>1</td>
<td>5</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Non-preferred</td>
<td>3</td>
<td>6</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Preferred</td>
<td>4</td>
<td>7</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Non-preferred</td>
<td>2</td>
<td>8</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

A one-way RM ANOVA was performed for the other two dependent variables (total hip roll angle and ASI) for comparison across the four conditions. In all cases, Bonferroni adjusted post-hoc t-tests were performed to further investigate significant main or interaction effects. A value of $p < 0.05$ was considered to be statistically significant for all trials for the RM ANOVA comparisons (significant main and interaction effects).
4. RESULTS

A representative example of hip roll angle for a single length is presented in Figure 5, whilst a representative example of hip roll angle for an entire trial (4 lengths) is presented in Figure 6.

Figure 5. Representative continuous hip roll angle for one length of a non-breathing trial for a single subject.
Figure 6. Representative continuous hip roll angle for one 100m bilateral breathing trial for a single subject.
The mean (SD) data for the participants’ age, height, weight, 100m season’s best (SB) time, mean trial time, trial time as % of SB time and mean velocity are shown in Table 3.

Table 3. Participant anthropometric and time trial data

<table>
<thead>
<tr>
<th></th>
<th>Males</th>
<th>Females</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>19.4 (2.0)</td>
<td>19.1 (1.0)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>180.8 (7.8)</td>
<td>171.4 (3.1)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>79.7 (8.2)</td>
<td>67.3 (7.2)</td>
</tr>
<tr>
<td>100m SB (s)</td>
<td>55.2 (1.9)</td>
<td>59.0 (2.4)</td>
</tr>
<tr>
<td>Trial Time (s)</td>
<td>73.7 (3.0)</td>
<td>76.5 (3.0)</td>
</tr>
<tr>
<td>% of SB</td>
<td>74.9 (0.02)</td>
<td>77.2 (0.02)</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>1.36 (0.06)</td>
<td>1.31 (0.02)</td>
</tr>
</tbody>
</table>
The first one-way repeated measures ANOVA that used condition (unilateral preferred, unilateral non-preferred, bilateral and non-breathing) as the within-subject variable determined that there was no significant main effect for time $F(3, 17) = 0.67, p=.57$ (Table 4). Therefore, the speeds of the trials were homogeneous and could be compared. A one-way RM ANOVA was also performed for each condition using length as the within-subject variable to determine whether there were any differences in body roll angle between lengths for each 100 m trial. The results showed that no significant differences in peak hip roll angle existed between lengths for any of the conditions (Table 5). Therefore, the mean hip roll angles (i.e., the average hip roll angle for the four lengths of each trial/condition) could be used for further analysis.

Table 4. Mean trial time by condition

<table>
<thead>
<tr>
<th>Condition</th>
<th>Preferred</th>
<th>Non-Preferred</th>
<th>Bilateral</th>
<th>Snorkel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (s)</td>
<td>74.7±3.6</td>
<td>75.1±3.0</td>
<td>74.0±3.6</td>
<td>75.5±3.6</td>
</tr>
</tbody>
</table>
Table 5. Peak hip roll angle by condition and length

<table>
<thead>
<tr>
<th>Condition/Side</th>
<th>Length 1</th>
<th>Length 2</th>
<th>Length 3</th>
<th>Length 4</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preferred</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preferred (B)</td>
<td>62.9±6.6</td>
<td>63.4±7.1</td>
<td>62.9±7.1</td>
<td>63.3±6.4</td>
<td>F=0.03, ( p &gt; .99 )</td>
</tr>
<tr>
<td>Non-Preferred (NB)</td>
<td>51.4±7.8</td>
<td>51.8±7.2</td>
<td>51.6±8.2</td>
<td>51.9±8.6</td>
<td>F=0.11, ( p &gt; .95 )</td>
</tr>
<tr>
<td>Non-Preferred</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preferred (NB)</td>
<td>53.9±8.7</td>
<td>54.6±9.3</td>
<td>54.2±9.5</td>
<td>54.6±9.6</td>
<td>F=0.14, ( p &gt; .94 )</td>
</tr>
<tr>
<td>Non-Preferred (B)</td>
<td>64.8±9.2</td>
<td>64.0±8.7</td>
<td>64.6±9.0</td>
<td>64.3±9.1</td>
<td>F=0.13, ( p &gt; .94 )</td>
</tr>
<tr>
<td>Bilateral</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preferred (B)</td>
<td>62.2±7.3</td>
<td>62.9±6.6</td>
<td>63.0±6.3</td>
<td>63.0±6.4</td>
<td>F=0.17, ( p &gt; .91 )</td>
</tr>
<tr>
<td>Non-Preferred (NB)</td>
<td>54.0±7.1</td>
<td>54.3±6.5</td>
<td>54.1±6.5</td>
<td>54.5±7.2</td>
<td>F=0.02, ( p &gt; .99 )</td>
</tr>
<tr>
<td>Bilateral</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preferred (NB)</td>
<td>54.0±7.3</td>
<td>53.6±6.5</td>
<td>53.6±6.6</td>
<td>53.9±6.7</td>
<td>F=0.14, ( p &gt; .94 )</td>
</tr>
<tr>
<td>Non-Preferred (B)</td>
<td>63.4±7.21</td>
<td>63.8±6.8</td>
<td>63.7±6.7</td>
<td>63.9±6.6</td>
<td>F=0.11, ( p &gt; .95 )</td>
</tr>
<tr>
<td>Non-Breathing (Snorkel)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preferred</td>
<td>52.0±7.3</td>
<td>52.0±7.2</td>
<td>51.9±7.3</td>
<td>52.4±7.3</td>
<td>F=0.11, ( p &gt; .95 )</td>
</tr>
<tr>
<td>Non-Preferred</td>
<td>55.4±8.1</td>
<td>56.9±7.6</td>
<td>56.3±7.6</td>
<td>56.2±7.7</td>
<td>F=0.01, ( p &gt; .99 )</td>
</tr>
</tbody>
</table>

Note: All hip roll values presented in degrees (°). Breath (B), Non-Breath (NB)
With respect to the results of the one-way RM ANOVAs that examined the effect of breathing condition, the results for total hip roll angle showed that there was a significant main effect for condition, $F(3, 17) = 32.01, p = .001$ (Figure 7).

Subsequently, the Bonferroni post-hoc analysis revealed that total hip roll angle was significantly greater ($p<0.01$) in the preferred, non-preferred and bilateral conditions compared to the non-breathing condition. In addition, the total hip roll angle in the non-preferred condition was significantly greater ($p<0.01$) than the preferred condition and the difference between the preferred and bilateral conditions approached significance ($p=0.06$).

![Figure 7](image)

**Figure 7.** Mean total hip roll angle for each breathing condition. Error bars indicate ±1 standard deviation.

* Significantly greater ($p < .05$) than preferred condition

# Significantly greater ($p < .05$) than non-breathing condition
A two-way RM ANOVA was also performed for peak hip roll angle with condition (unilateral and bilateral) as the within-subject repeated measures variable and body side (preferred vs. non-preferred) and breath (breathing vs. non-breathing) as the independent variables. Significant main effects were found for condition, \( F (3, 17) = 16.20, p=.001 \) and breathing, \( F (1, 19) = 298.32, p=.001 \). There was no significant main effect for side \( F (1, 19) = 0.031, p=.861 \). Significant interaction effects were also found for condition*breathing \( F (3, 17) = 4.29, p=.02 \) and condition*side \( F (3, 17) = 109.32, p=.001 \). Subsequent paired t-tests were performed to determine the effect of breathing on mean peak hip roll angle. The values and pairings of these t-tests are shown in Table 6. In each condition, the mean peak hip roll angle to the breathing side was significantly greater \( (p<.001) \) than the non-breathing side (Figure 8). For example, the preferred side (breathing side) was significantly greater \( (p<0.001) \) than the non-preferred side (non-breathing) in the preferred condition. Similarly, the non-preferred side (breathing) was significantly greater \( (p<0.001) \) than the preferred side (non-breathing) in the non-preferred condition. In the bilateral breathing condition, the roll angles for breathing were significantly greater \( (p<0.001) \) than the angles for non-breathing for both the preferred and non-preferred sides.
Figure 8. Mean peak hip roll angle according to side and condition. Error bars indicate ±1 standard deviation.

*Significantly greater (p < .05) than non-breathing side

# Significantly greater (p < .05) than preferred side.

For each condition, the preferred side (P) is shown first followed by the non-preferred side (NP) as the breathing (B) or non-breathing (NB) side.
Table 6. Mean peak hip roll angles for breathing vs. non-breathing sides

<table>
<thead>
<tr>
<th>Condition</th>
<th>Breathing Side (°)</th>
<th>Non-Breathing Side (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preferred</td>
<td>63.1 (7.1)*</td>
<td>51.7 (7.3)</td>
</tr>
<tr>
<td>Non-Preferred</td>
<td>64.5 (7.2)*</td>
<td>54.3 (8.0)</td>
</tr>
<tr>
<td>Bilateral (Preferred)</td>
<td>62.8 (7.5)*</td>
<td>54.2 (7.5)</td>
</tr>
<tr>
<td>Bilateral (Non-Preferred)</td>
<td>63.8 (7.2)*</td>
<td>53.8 (7.4)</td>
</tr>
</tbody>
</table>

*Significantly greater (p < .05) than non-breathing side

The next two-way RM ANOVA compared all non-breathing peak hip roll angle means across all four conditions. No significant main effect was evident for condition $F(2, 18) = 2.24, \ p=.135$, however a significant main effect was found for side $F(1, 19) = 6.08, \ p=.02$. A significant interaction effect was also found for condition*side $F(2, 18) = 40.84, \ p=.001$. Subsequently, a Bonferroni post-hoc analysis revealed that mean peak hip roll was significantly greater to the non-preferred side ($p<.05$) than the preferred side. Paired sample t-tests were performed to determine the interaction effect of condition and side by comparing mean peak hip roll angle in the unilateral (i.e., preferred and non-preferred), bilateral and non-breathing conditions (Figure 9). In the unilateral conditions, mean peak hip roll angle was significantly greater ($p<.001$) to the preferred side than the non-preferred side. In the non-breathing condition, mean peak hip roll angle was significantly greater ($p<.001$) to the non-preferred side than the preferred side. In the bilateral condition, mean (non-breathing) peak hip roll angles were not significantly different between preferred and non-preferred sides ($p>.22$).
Figure 9. Results of t-tests comparing mean non-breathing peak hip roll angles according to side and condition. Error bars indicate ±1 standard deviation.

*Significantly greater (p < .05) than non-preferred side

# Significantly greater (p < .05) than preferred side.
With respect to the ASI results, a positive value indicates asymmetry to the preferred side and a negative value indicates asymmetry to the non-preferred side. The ASI results indicated that asymmetry was highest in the preferred condition (20.2%), followed by the non-preferred (-17.5%) and non-breathing conditions (-7.7%), whilst the bilateral condition demonstrated the least asymmetry (-4.1%) as seen in Figure 10. The results of the RM ANOVA for ASI demonstrated a significant main effect for condition F(3, 17) =36.04, p=.001 (Figure 10). Subsequent Bonferroni post-hoc analysis demonstrated that the ASI in the bilateral condition was significantly lower (p<.01) than the preferred, non-preferred and non-breathing conditions. The preferred and non-preferred conditions also demonstrated significantly greater (p<.01) ASI than the non-breathing condition.
Figure 10. Asymmetry index (ASI) according to condition. Error bars indicate ±1 standard deviation.

* significantly greater (p < .01) than the non-breathing condition

# significantly greater (p < .01) than the bilateral condition
5. DISCUSSION

The purpose of this study was to investigate the effect of breathing on body roll in competitive front crawl swimming using a single, body-fixed, tri-axial accelerometer. The primary findings of the study were: 1) that total hip roll angle was significantly greater in each of the three breathing conditions compared to the non-breathing condition. Furthermore, total hip roll angle was significantly greater in the unilateral non-preferred condition compared to the unilateral preferred condition. 2) Peak hip roll angle was significantly greater when breathing than when not breathing in the unilateral preferred, unilateral non-preferred and bilateral conditions. 3) Peak hip roll angle was significantly greater to the non-preferred side in the non-breathing condition but significantly less than the preferred side in the unilateral non-breathing conditions. 4) Bilateral asymmetry, as measured by the ASI, was significantly greater in the two unilateral conditions compared to the non-breathing and bilateral conditions. Furthermore, the non-breathing condition exhibited significantly greater asymmetry than the bilateral condition.

5.1 Use of an Accelerometer

The use of a single, body-fixed, tri-axial accelerometer is a new approach to body roll angle measurement. A similar method has been used in a previous study (Bachlin & Troster, 2012), however, the current study is the first to conduct an experimental investigation involving an accelerometer and body roll angles. The peak hip roll angle from a single length (non-breathing condition) of a representative trial can be seen in Figure 5. The initial jump and push off can be seen as a sharp spike followed by a
relatively flat orientation as the swimmer glides off the wall, face-down, in a streamlined position. This is followed by a sinusoidal pattern in the roll angle as the swimmer’s body alternately rolls to each side. In Figure 5, the negative values represent the roll to the preferred side (left side of the body; counter-clockwise) and the positive values represent the roll to the non-preferred side (right side of the body; clockwise). The finding of a significantly greater peak hip roll to the non-preferred side when not breathing is apparent. Figure 5 also shows a count of 9 complete stroke cycles (i.e., one stroke cycle is the roll to the non-preferred and preferred sides combined) in a 25m length. This continuous measurement of data was one of the benefits expected by using an accelerometer.

A complete 100m trial (4 lengths) in the bilateral breathing condition is presented in Figure 6. The initial push-off and glide are the same as shown in Figure 5. However, in the bilateral condition a breath is followed by two non-breaths before the next breath on the contralateral side. The pattern of hip roll and difference in peak hip roll angle for breaths and non-breaths is visually apparent. At the end of each length a large positive and negative spike occurs as the swimmer flip-turns to begin the next length.

The data from the pilot investigation (see Appendix B) suggested that the accelerometer method of angle calculation was valid when compared to the video method. Further, the mean total hip roll angle values from the current study are similar to those reported for previous video (Castro et al., 2006) and 3D studies (Psycharakis & Sanders, 2008; Psycharakis & McCabe, 2011). However, the peak hip roll angle values differed slightly compared to previous studies and the possible causes, such as velocity, experimental conditions and sensor placement, are discussed in sections 5.2 and 5.3.
While there might be some difference in the peak roll angles that were measured, the pattern of a significantly greater peak hip roll angle on the breathing side compared to the non-breathing side was identified with the accelerometer and can be seen visually when looking at the graphs of the angle data in Figures 5 and 6. Consequently, the accelerometer provides an effective method for quantifying relative hip roll angle differences between sides and conditions.

5.2 Total hip roll angle

The results demonstrate that the total hip roll angle was significantly greater in the three breathing conditions compared to the non-breathing condition. This shows that breathing affects hip roll such that the total roll angle is greater when breathing occurs as part of the stroke cycle. This pattern is similar to previous studies which found a greater magnitude of total roll angle in breathing conditions compare to non-breathing conditions (Castro et al., 2006; Psycharakis & McCabe, 2011). Total hip roll angle was significantly greater in the unilateral, non-preferred condition than the preferred condition. This is explained by a significantly greater non-breathing peak hip roll angle to the preferred side (54.3°) compared to the non-preferred side (51.7°) in the unilateral conditions. This supports the hypothesis that body roll is greater to the preferred side when breathing occurs unilaterally.

The magnitudes of total hip roll angle (i.e., left plus right) found in this study (108.3°-118.8°) are greater than those previously reported in other studies. For example, Psycharakis & Sanders (2008) reported a mean value of 50.4° for non-breathing hip roll angle, however this was recorded at a higher velocity (1.53 m/s) in a maximal 200m
effort and subjects were instructed not to breathe throughout the recording zone. Similarly, Psycharakis & McCabe (2011) recorded values of 43.9° and 39.8° for breathing and non-breathing trials in a maximal 25m trial at velocities of 1.76 m/s and 1.81 m/s, respectively. Interestingly, mean total shoulder roll angle values of 106.6° (Psycharakis & Sanders, 2008) and 105.1° (Psycharakis & McCabe, 2011) were reported, which are similar to the hip roll angles presented in the current study.

A possible explanation for the difference in total hip roll angle is the velocity of the trials. Castro et al. (2006) demonstrated that as velocity increases, body roll angle decreases. Similarly, Psycharakis & Sanders (2008) observed that a 0.23 m/s decrease in velocity throughout 200m caused an increase of 10.2° in hip roll angle. The mean velocity of the current study was 1.34 ± 0.06 m/s, so it is reasonable to expect that larger hip roll angles would be recorded, although it may not have been the only source of difference between these angles and those previously reported in the literature.

Another possible explanation for the variations in hip roll angle is that the studies by Psycharakis & Sanders (2008) and Psycharakis & McCabe (2011) required subjects to control their breathing patterns through a 6.75m³ recording zone. The restriction of not breathing for part of the length may have disrupted the natural stroke cycle rhythm. Another restriction of these studies is that only one stroke cycle per length was analyzed. In the current study, approximately 8 stroke cycles were analyzed per length, per trial. Therefore, data was collected for approximately 32 stroke cycles per subject per trial, compared to 4 (Psycharakis & Sanders, 2008) and 1 (Psycharakis & McCabe, 2011) per trial in the previous studies.
It is possible that the placement of the accelerometer may have also caused a larger value for hip roll angle. The sensor placement at L5/S1 is superior to the position of a line projected from hip markers described in previous 3D studies (Psycharakis & Sanders, 2008; Psycharakis & McCabe, 2011). Consequently, this placement may have resulted in the measurement of greater values for hip roll angle. Placing the accelerometer any lower on the hips of an athlete is not practical, as the sensor would have been placed over the buttocks. As a swimmer’s kick originates from the hip flexors and gluteals, sensor placement over this area would have resulted in constant movement of the sensor which would have affected the accuracy of the signal.

5.3 Peak Hip Roll angle

To further understand the effects of laterality (i.e., body side) and breathing on hip roll angle, the total hip roll angle values were separated into hip roll angles for each side. The results (Figure 8) showed that peak hip roll angle was significantly greater to the breathing side compared to the non-breathing side in the preferred, non-preferred and bilateral conditions. Psycharakis & McCabe (2011) found no significant differences between breathing and non-breathing sides when a group of 10 participants swam at maximal velocity. It is likely that the very fast speed used in these trials reduced the hip roll angle to the point where breathing was no longer a factor. The authors also state that significance might have been achieved had they included more participants (n=10). A strength of the current study was that the larger sample size (n=20) provided sufficient statistical power to detect existing differences between breathing and non-breathing conditions.
A result that was not expected was the significant difference in peak hip roll angle in the non-breathing condition. The non-breathing trial was designed to be a control trial to remove the asymmetry caused by breathing. It was found that peak hip roll angle to the non-preferred side (56.2 ± 6.8°) was significantly greater than the roll to the preferred side (52.1 ± 6.1°) in the non-breathing condition. This suggests an underlying body roll asymmetry (not related to breathing) that affects the stroke mechanics of front crawl. Interestingly, this result is contradictory to the results of the unilateral breathing conditions, in which the non-breathing hip roll angle of the preferred side (non-preferred condition) was significantly greater (2.6°) than the non-preferred side (preferred condition). Although it is difficult to explain the precise reason for the discrepancy in these findings, the results suggest that the difference is likely related in some way to the presence (or absence) of breathing.

It was hypothesized that the degree of body roll angle would not be equal for breathing to the preferred side vs. breathing to the non-preferred side in the unilateral breathing conditions, and that the degree of body roll angle would be larger to the preferred side in both conditions. However, this was not the case. The peak hip roll angles to the breathing and non-breathing sides in each condition are shown in Table 6. It can be seen that the mean peak hip roll angles for the unilateral conditions involving breathing varied by only 1.7°, and across the three breathing conditions the peak hip roll angle to the non-preferred side was actually greater in the non-preferred and bilateral conditions. These results suggest that the influence of breathing (i.e., taking or not taking a breath) has a greater effect on body roll angle than the influence of laterality (i.e., the preference to roll to one side more than the other).
It should also be noted that the non-breathing angle in the preferred condition was significantly lower than the non-preferred condition and lower (4.5°) than the roll to the non-preferred side in the snorkel (non-breathing) condition. Therefore, in the breathing conditions, the least amount of hip rotation occurred when the participants were not breathing and were rolling to the non-preferred side. When considering the cause of the significant difference in total hip roll angle between the preferred and non-preferred conditions, the results show that this occurred because of significantly greater hip roll to the preferred side when not breathing than to the non-preferred side when not breathing. This suggests the presence of laterality in favour of the preferred side, when not breathing in unilateral breathing conditions (i.e., conditions in which the roll is asymmetric due to the effect of breathing). The hypothesized pattern for the unilateral preferred breathing condition vs. the unilateral non-preferred condition was shown to be incorrect as the expected difference, a greater hip roll angle to the preferred side in both conditions (whether breathing or not breathing) did not occur. Instead, the opposite pattern occurred, such that the extent of body roll to either side was strongly influenced by breathing, regardless of whether the breathing occurred to the preferred side or the non-preferred side. This relationship was also observed for the bilateral breathing condition, which resulted in greater hip roll angles to the breathing side, irrespective of whether it was on the preferred or the non-preferred side. As expected, the results also demonstrated that bilateral breathing balances the body roll so that there is less roll asymmetry than occurs when breathing unilaterally, regardless of the side to which the unilateral breathing occurs.
5.4 Bilateral asymmetry

It was hypothesized that the unilateral breathing patterns would demonstrate an asymmetry in hip roll angle between the preferred and non-preferred sides. This hypothesis proved correct in that for the preferred and non-preferred breathing conditions, the hip roll to the breathing side was significantly greater than to the non-breathing side, resulting in a significant bilateral roll asymmetry. This was shown by calculating the ASI, such that the preferred condition demonstrated the highest ASI (20.2%), followed by the non-preferred condition (-17.5%). It is interesting to note that the absolute level of asymmetry for unilateral breathing was similar despite the fact that the total hip roll angle of the non-preferred condition was significantly greater than the preferred condition.

In the bilateral breathing condition, it was expected that the body roll angle would approach symmetry and be less asymmetric than when breathing unilaterally. The peak hip roll angle for the preferred and non-preferred sides was similar for breathing (62.8° vs. 63.7°) and not breathing (53.8° vs. 54.2°). When looking at the ASI for the bilateral condition, the mean hip roll angles to the preferred side (i.e., breaths and non-breaths) were combined and compared to the angles for the non-preferred side (breaths and non-breaths). This resulted in an ASI of -4.1% to the non-preferred side, which was significantly lower than the other three conditions. The bilateral breathing pattern appears to neutralize the effect of breathing on asymmetry, as the rolling pattern of the swimmer is balanced as the breathing alternates from side to side (i.e., breathing every 3 strokes or 1.5 stroke cycles). Therefore, by breathing to both sides, there is less roll asymmetry than when breathing to one side only. When not breathing, the subjects rolled
significantly more to the non-preferred side than to the preferred side. This finding was unexpected, and as such is difficult to explain. Whilst it was significantly greater than the bilateral condition, the ASI for the non-breathing side was significantly less than the two unilateral conditions. This demonstrates that the non-breathing condition was more symmetrical than the unilateral conditions but unexpectedly, not as symmetrical as the bilateral condition.

The moderately asymmetric hip roll pattern in the non-breathing condition (and to a lesser extent in the bilateral breathing condition) suggests that there may be an underlying mechanism (other than breathing) that is responsible for body roll asymmetry. Psycharakis and Sanders (2008) found that swimmers rolled their shoulders significantly more to the non-preferred side in a non-breathing stroke cycle during a maximal 200m effort. They suggested that the increased roll to the non-preferred side could be due to a difference in the magnitude, duration, timing or direction of the propulsive forces of the dominant arm. Studies that have investigated bilateral asymmetry in other cyclic movements such as walking, running and cycling have suggested that the dominant limb produces greater force than the non-dominant limb (Sadeghi et al., 2000; Carpes et al., 2011). Therefore, it is conceivable that propulsive force asymmetry in the arms and/or differences in shoulder roll may be a possible cause of the hip roll asymmetry seen in the non-breathing trials.
5.5 Practical applications and future research

This study has several important findings that provide a basis for both practical application and future research. First, an important relationship between breathing and hip roll angle has been established. Previous research investigated either the preferred side, breathing or non-breathing conditions, but none compared preferred, non-preferred, bilateral and non-breathing conditions in the same study. It can be stated that at lower intensities (i.e., at a self-selected, submaximal speed), unilateral breathing is associated with an asymmetrical hip roll pattern, whereas non-breathing and bilateral breathing conditions reduce asymmetry. Therefore, swimmers should be encouraged to adopt a bilateral breathing pattern in training so as to reduce the asymmetry of their hip roll, and potentially the asymmetry of their stroke.

Second, a significantly greater peak hip roll angle to the non-preferred side compared to the preferred side in the non-breathing condition has not been reported previously. This suggests the presence of a second, underlying mechanism that affects the rolling movement of a swimmer when the effect of breathing is removed. Further research is needed to investigate whether this occurs as the result of a difference in propulsion (for e.g., strength), anthropometry (e.g., range of motion, limb length) or motor control (e.g., laterality and/or technique). Additionally, this study investigated hip roll angle and asymmetry at a single swimming speed with no fatigue, and as such future research should attempt to determine the effect of increased velocity and fatigue on hip roll angles and asymmetry.
Finally, the use of an accelerometer (and possibly other inertial sensors) provides the opportunity for research in aquatic environments to take a significant step forward. Inertial sensors are relatively cheap and easy to use, with many handheld devices (e.g. smart phones) already benefiting from their presence. With appropriate software, coaches will be able to track athletes’ training and competition throughout a season or career. This could be used to determine how technical changes or training volumes affect stroke characteristics such as body roll angle and asymmetry. It also has the potential to be used as an injury screening tool to determine pre- and post-injury changes in hip roll mechanics in individual swimmers.
6. CONCLUSION

The results of this study demonstrate that breathing has a substantial effect on hip roll angle and asymmetry in front crawl swimming such that: 1) Swimmers roll their hips significantly more when breathing than when not breathing, 2) unilateral breathing patterns are significantly more asymmetric than bilateral or non-breathing patterns and 3), if swimmers train with a snorkel, which eliminates the effect of breathing, swimmers will roll their hips significantly more to the non-preferred side than to the preferred side. The findings of this study suggest that other factors, in addition to breathing, have an effect on hip roll angle and asymmetry and that further research should attempt to investigate the extent to which these findings are consistent at different (i.e., faster) swimming velocities and conditions (e.g., fatigue).
7. REFERENCES


Appendix A

CONSENT FORM

The effects of breathing on body roll asymmetry in competitive front crawl swimming

Investigators:

Dr. John Barden
Faculty of Kin. & Health Studies
University of Regina
Regina, SK S4S 0A2
Phone: (306) 585-4629
E-mail: john.barden@uregina.ca

Michael Barber
Faculty of Kin. & Health Studies
University of Regina
Regina, SK S4S 0A2
Phone: (306) 520-7236
E-mail: barberathletic@gmail.com

To be completed by the participant:

Have you read and received a copy of the attached Information Sheet      Yes/No
Do you understand the benefits and risks involved in taking part in this research study?  Yes/No
Have you had an opportunity to ask questions regarding the study?            Yes/No
Do you understand that you are free to refuse to participate or withdraw from the study at any time? Yes/No
Has the issue of confidentiality been explained to you?                            Yes/No
When you swim freestyle (front crawl) what is your preferred breathing side?      Left/Right
When you first learned how to swim, which side did you breathe on?               Left/Right

This study was explained to me by: ______________________

I agree to take part in this study.

_________________________          __________________________          ____________
Signature of participant             Date                           Witness

_________________________          __________________________
Printed Name                        Date                            Printed Name

I believe that the person signing this form understands what is involved in the study and voluntarily agrees to participate.

_________________________          ____________
Signature of Investigator           Date
This project has been approved by the Research Ethics Board of the University of Regina. If you have any questions or concerns about your rights or treatment as a research participant, you may contact the Chair of the University Research Ethics Board by phone at 585-4775 or by e-mail at research.ethics@uregina.ca. Should you have any questions or wish to discuss the procedures or objectives of the study, please contact Michael Barber via phone (306) 520-7236 or e-mail (barberathletic@gmail.com).

THE INFORMATION SHEET MUST BE ATTACHED TO THIS CONSENT FORM AND A COPY GIVEN TO THE RESEARCH PARTICIPANT
INFORMATION SHEET

The effects of breathing on body roll asymmetry in competitive front crawl swimming

Investigators:
Dr. John Barden  
Faculty of Kin. & Health Studies  
University of Regina  
Regina, SK S4S 0A2  
Phone: (306) 585-4629  
E-mail: john.barden@uregina.ca

Michael Barber  
Faculty of Kin. & Health Studies  
University of Regina  
Regina, SK S4S 0A2  
Phone: (306) 520-7236  
E-mail: barberathletic@gmail.com

PURPOSE OF THE STUDY:

The purpose of this study is to determine the relationship between breathing and body roll angle in competitive front crawl swimming using a body-fixed tri-axial accelerometer. A secondary purpose is to determine the degree to which different breathing conditions affect body roll asymmetry.

BACKGROUND:

An efficient body roll pattern can reduce drag forces and increase propulsive forces, resulting in faster velocities and more efficient strokes. The breathing action of a swimmer facilitates the rolling motion of the body. The degree of body roll associated with different breathing conditions has not been investigated. Tri-axial accelerometers allow non-invasive, continuous measurement of data in an underwater environment. Quantifying body roll in various breathing conditions will provide data about stroke asymmetry and efficiency which can be used to improve technique and performance.

PROCEDURE:

Subjects will be required to perform 4 x 100 m front crawl swimming trials at 65% of season best 100 m time in a 25-metre pool. Each trial will involve a different breathing pattern (left side only, right side only, bilateral and snorkel). Subjects will then perform 100m trials at an increasing intensity of 75%, 85% and 95% of season best 100m time using the preferred breathing side only. A tri-axial accelerometer will be attached to the back at the hip with an elastic belt. The accelerometer will record data for each trial.

RISKS/BENEFITS:

There are no known risks involved with participating in this study. Your participation will help to provide important data on body roll and breathing patterns. This information can be
used by researchers and coaches to understand and improve technical models of front crawl swimming, and subsequently improve performance.

CONFIDENTIALITY/FREEDOM TO WITHDRAW:

Group averages rather than individual data will be reported. If it becomes necessary to report individual data, the data will be referred to via an anonymous subject code and trial number. Individual subject codes (e.g., Subject 1a) will be the only reference to any presentation of individual data. Only the investigators will have access to participant information. There are no circumstances that would require the investigators to directly identify any participants in the study. You are free to withdraw from the study at any time. Data from this study will not be used in future studies without further approval from an ethics committee.

If you have any questions about the study or wish to provide comments about the research and its procedure, please contact Michael Barber at (306) 520-7236 or via e-mail barberathletic@gmail.com; or Dr. John M. Barden at (306) 585-4629 or via e-mail at john.barden@uregina.ca.

Please sign below to indicate that you have read and understand the information described on this page.

__________________________________  ____________________________________
Signature of the Research Participant  Signature of the Investigator
Appendix B

Accelerometer vs. video validation of roll angle calculation

Purpose

A pilot investigation was performed to determine the accuracy of angular position calculations obtained from an accelerometer. To validate the method, accelerometer data was compared to data digitized from video.

Method

Four reflective markers were placed on a large cylindrical water jug that was approx. 20 cm in diameter. The markers were placed in a 12 cm by 12 cm square. A digital video camera (Sony, Minato, Japan) was mounted on a tripod and aligned perpendicular to the plane of motion. Prior to the experimental trial, the camera zone was calibrated using a reference frame of 20 cm by 20 cm aligned perpendicular to the camera in the sagittal plane. The accelerometer (GENEActiv, Cambridge, UK) was fixed to the water jug such that its z-axis was aligned through the midpoint of the square, the x-axis perpendicular to the camera and y-axis perpendicular to the x-axis. The accelerometer and camera were set to record at 50Hz.

Two trials were performed; 1) the water bottle was slowly rolled in the sagittal plane through 90 degrees to the left and right sides on a flat surface, 2) the water bottle was rolled in the sagittal plane through 90 degrees to the left and right sides on a 30° incline. The reason for the incline was to account for possible changes in roll angle due to changes in pitch angle during a swimmer’s motion.
The camera and accelerometer were both turned on. Prior to initiation of the trial, the investigator tapped the accelerometer to create a vertical spike. This instant was captured with the video camera and provided a point from which the data from the camera and accelerometer could be synchronized. The investigator then rolled the water jug on a flat table, using a handle attached to the posterior of the apparatus, through approximately 90° to the left and back past 0° to 90° to the right then back to 0°. Care was taken to ensure the water jug was rolled in the sagittal plane and rolled at a constant speed. This method was repeated for the 30° inclination after the camera was re-aligned and calibrated in the same plane as the movement of the water jug.

Post processing of the video was done using Peak Motus 9.2 (Vicon, Denver, USA). Each marker was digitized for the entire length of the trial. The raw X and Y coordinates were processed using a low-pass digital filter set at a cutoff frequency of 4 Hz in Microsoft Excel. Roll angle was calculated using the filtered data for the lower left and right markers and the following tangential equation;

\[ \text{Roll angle} = \arctan\left( \frac{Y - Y_0}{X - X_0} \right) \]

The raw X, Y and Z accelerations were processed using a low-pass digital filter set at a cutoff frequency of 4 Hz in Microsoft Excel. Roll angles were calculated using the filtered acceleration data and the following tangential equation;

\[ \text{Roll angle} = \arctan\left( \frac{Y - Y_0}{X - X_0} \right) \]
The video and accelerometer roll angles for each trial were compared using the root mean square error (RMSE) to quantify the difference between the two signals from the beginning to the end of the trial.

Results

The result of the angle calculation for the two methods can be seen below. Figure 1 shows the comparison of the flat trial and Figure 2 shows the comparison of the 30° angled condition.

Figure 1. Filtered roll angle of video vs. accelerometer for the flat trial.
The RMSE for the flat trial was 1.99° and the RMSE for the 30° angle trial was 1.82°. These results demonstrated that the values calculated for the accelerometer showed excellent agreement compared to the values calculated from the video. The RMSE was similar between the two trials. During the flat trial, as the water jug was reaching peak roll to the right, the investigator twitched, causing a slight deviation. This is reflected in the graph at the peak in the negative direction in which both signals deviate towards zero before reaching the peak negative value. The ability of the accelerometer to measure the slight deviation in the movement of the water jug confirms that it is able to detect very small changes in rotation to a degree equal to that of the standard method (i.e., videography).
Conclusion

The results of this validation procedure demonstrated a low RMSE between the accelerometer and video method of angle calculation in both conditions. These results suggest that the accelerometer method of angle calculation is similar to the video method of angle calculation in two different positions (zero and 30° orientations about the pitch axis). Therefore, it is reasonable to conclude that the accelerometer can be used to measure body roll angles in front crawl swimming with a high level of confidence that is equal to that of 2D camera methods.