BODY ROLL DIFFERENCES IN FREESTYLE SWIMMING BETWEEN
SWIMMERS WITH AND WITHOUT SHOULDER PAIN

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By
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Oscar Vila Dieguez, candidate for the degree of Master of Science in Kinesiology & Health Studies, has presented a thesis titled, *Body Roll Differences in Freestyle Swimming Between Swimmers With and Without Shoulder Pain*, in an oral examination held on December 20, 2018. The following committee members have found the thesis acceptable in form and content, and that the candidate demonstrated satisfactory knowledge of the subject material.

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Abstract

Shoulder pain is the most common complaint for swimmers of any level, the prevalence of which is reported to be between 40% and 91%. The term ‘‘swimmer’s shoulder’’ covers a spectrum of coexisting pathologies, with rotator cuff–related pain being the most common finding. Among many other variables, body roll has been proposed as a potential variable affecting shoulder pain, due to its potential to modify hand path and upper limb kinematics. This study aimed to identify potential differences in body roll between swimmers with and without shoulder pain. 24 competitive swimmers (21.5±4.8 years old) were recruited from several teams in Northern Spain. 12 were experiencing unilateral shoulder pain (6 male, 6 female) and 12 were healthy swimmers (6 male, 6 female). Their body roll was measured during 3 sets of 100m front crawl swimming at three different speeds (slow, medium and fast). For this purpose, two tri-axial accelerometers were used, one at the shoulder level and one at the hip level to obtain body roll angles at these two different regions. The results showed no significant difference between the pain group and the control group for the breathing side roll at the shoulders (77.8° vs 80.3°) nor at the hips (62.9° vs 65°). Regarding the non-breathing side, swimmers with shoulder pain rolled significantly less than the control group at the hips (48.8° vs 56.7°, p=0.018, r=0.931), and no significant difference was found at the shoulders. These findings suggest that a potential relationship between hip rotation and shoulder pain may exist, but no cause-effect relationship can be inferred from this study due to its cross-sectional nature, and only one subgroup of shoulder participants (from a biomechanical perspective) was analyzed. Prospective studies should be carried out to further investigate the mechanisms associated with this relationship.
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1. INTRODUCTION

Swimming is one of the most popular sports across different segments of the general population. There is an extensive range of participants, from those who swim only occasionally for recreational purposes to those who swim regularly for fitness and to those who compete at national and international levels. The buoyant effect of water lends itself to a reduced risk of injury among those who partake at a recreational level. However, numerous articles describe injuries among competitive and elite swimmers (Gaunt & Maffulli, 2012), the most significant of which is shoulder pain.

Shoulder pain is the most common complaint for swimmers of any level, the prevalence of which is reported to be between 40% and 91% (Wanivenhaus, Fox, Chaudhury, & Rodeo, 2012). The term ‘‘swimmer’s shoulder’’ covers a spectrum of consecutive or coexisting pathologies, with rotator cuff–related pain being the most common finding (Bak, 2010). The impingement of the supraspinatus and long head of the biceps tendons have been proposed as a major cause of the shoulder problems that often occur among freestyle and butterfly swimmers (Gaunt & Maffulli, 2012). Some of the shoulder movements used in freestyle swimming are believed to cause impingement of those structures and provide the primary mechanism for the development of rotator cuff pathology (Yanai, T., Hay, & Miller, 2000). At the same time, these movements are affected by a number of different variables including arm position, body roll and breathing (Liu, Hay, & Andrews, 1993; Psycharakis & McCabe, 2011; Vezos et al., 2007; Yanai, Toshimasa, 2001). The alternation between left and right arm strokes in freestyle swimming is accompanied by rotations of the
trunk around its longitudinal axis. These rotations are commonly known as body roll. Body roll has important functions in freestyle swimming, such as facilitating the breathing action and recovery of the arm, as well as affecting the underwater hand path (Psycharakis & McCabe, 2011). It has been suggested that body roll is linked to swimming performance and the etiology of swimmer’s shoulder (Davies, G. J., Matheson, Ellenbecker, & Manske, 2008; Penny & Smith, 1980; Weldon & Richardson, 2001). However, no strong evidence can be found with respect to the relationship between shoulder injury and body roll, although some authors have found differences in body roll between healthy and injured swimmers (Beekman, 1988).

It is not unusual for competitive swimmers to have body roll asymmetries when performing the front crawl stroke (a.k.a. freestyle), and asymmetry is an important issue both in swimming biomechanics (i.e., asymmetry of breathing, kicking and arm kinematics) and shoulder injuries (i.e., asymmetry of pain distribution). Between 59 and 85 per cent of the swimmers with shoulder pain have unilateral pain, and some authors have tried to explain these findings by looking for a relationship with asymmetry during swimming (Bak & Fauno, 1997; Richardson, Jobe, & Collins, 1980; Sein et al., 2010). Breathing seems to be one of the contributors to the asymmetry of the stroke in freestyle (Sanders, Thow, & Fairweather, 2011; Seifert, Chollet, & Allard, 2005) as it modifies the upper limb position and the handpath during the stroke (Vezos et al., 2007). However, no strong relationship with shoulder pain has been found. Many authors state that questions about how asymmetries affect performance and injury risk still remain unanswered and require further investigation (Sanders et al., 2011).
Researchers have tried to look for answers by analyzing variables such as body roll, breathing and stroke asymmetry, and by looking at the stroke kinematics and exploring how they affect each other (Vezos et al., 2007). For this purpose, the use of technology for detailed biomechanical analysis and technical refinement plays an important role. Indeed, the use of video cameras or sensors for capturing, modeling and fine-tuning swimming strokes has become a common requirement for the biomechanical analysis of swimming. The traditional gold-standard method for swim motion analysis is primarily video-based. This is typically performed by recording a raw video sequence, sometimes with reflective markers attached to the swimmer, and tracking the points of interest using specific computer software. The points tracked typically include articulations at the wrist, elbow and shoulder. This process is difficult to fully automate and tends to be error-prone (Callaway, Cobb, & Jones, 2009). Although this can provide the swimmers and coaches with detailed motion analysis, it is very expensive and requires time-consuming system installation and calibration and intensive data processing. In particular, bubbles due to water turbulence represent a significant issue for underwater tracking. As an alternative, wearable sensors have increased in popularity in recent years, as they do not require a complicated setup in the swimming pool (Magalhaes, Vannozzi, Gatta, & Fantozzi, 2015). They are also swimmer-centric which allows researchers to analyze multiple stroke cycles per length and gather a more complete picture of how stroke characteristics change throughout each length or an entire race (Pansiot, Lo, & Yang, 2010).

Inertial measurement units (IMU) can also be used for different kinds of biomechanical analyses. IMUs are electronic devices comprised of an accelerometer,
a rate gyroscope and a magnetometer, which measure the tri-axial linear acceleration, angular velocity and components of the earth’s magnetic field, respectively (Callaway et al., 2009). Recently, Magalhaes (2014) explored the joint kinematics of the upper limb using IMUs attached to each segment and compared it to a video-based laboratory swimming simulation and obtained similar results with both methods. From both a sports conditioning and clinical perspective, the knowledge of joint kinematics during swimming provides useful information. In the first case, it can give essential information for planning a training program specific for each athlete. Moreover, measuring biomechanical variables throughout a whole race or training session is useful to prevent overtraining and provide the coach with athlete specific data. Concerning the clinical aspects of shoulder pain, a biomechanical analysis can support the design of appropriate prevention programs for the most common upper limb injuries that typically affect swimmers (Magalhaes, 2014).

The purpose of the current study, therefore, is to investigate the relationship between body roll angle and shoulder pain in elite competitive freestyle swimmers. This study will look for body roll asymmetries to determine whether those variables are similar in swimmers with pain compared to swimmers without pain (control group).

It is hypothesized that swimmers with unilateral pain will share certain characteristics of body roll asymmetry, which will be different from the swimmers without pain. Specifically, the first hypothesis is that swimmers with a preferred breathing side that is opposite to the shoulder with pain will have less body roll to the side of the affected shoulder compared to swimmers without pain. A second
hypothesis is that swimmers within the unilateral shoulder pain group will have a greater body roll asymmetry compared to the control group, irrespective of breathing. These hypotheses are formulated based on two mechanisms that could be harmful for swimmers who have this pattern of preferred breathing side and contralateral pain. First, as described by Richardson et al. (1980), an insufficient body roll to one side causes an augmented horizontal abduction of the ipsilateral arm during the recovery phase. This increases the potential impingement of the long head of the biceps and supraspinatus tendons on the coracoacromial arch. Second, having a substantially greater body roll to the preferred breathing side causes the arm of the opposite side to pull through a longer distance. This potentially increases the muscle workload and fatigue on this side. In addition, the extra work on this side could weaken the capsuloligamentous complex. Turkel, Pauio, Marshall and Girgis (1981) have stated that during the early pull-through phase the shoulder is in maximum abduction/flexion and external rotation, such that the load on the capsuloligamentous complex is at its highest point during the stroke cycle.

In summary, this study will attempt to determine whether: 1) freestyle swimmers with unilateral shoulder pain, whose preferred breathing side is opposite to the affected shoulder, roll less to the affected side and 2) if body roll asymmetry is greater in freestyle swimmers with unilateral shoulder pain compared to swimmers without pain.
2. LITERATURE REVIEW

2.1 Swimming biomechanics

Biomechanics is an important part of swimming research. Understanding how the human body behaves in the water in the act of swimming provides information that can be used to maximize performance and minimize the risk of injury. In this section, stroke mechanics, drag forces and upper limb mechanics will be reviewed in order to describe the relationship between swimming biomechanics and injuries of the upper limb.

2.1.1 Stroke cycle phases

The most commonly used stroke in swimming is front crawl, also called freestyle (Richardson et al., 1980). Broadly speaking, there are four phases for each stroke cycle of freestyle: catch, pull, push and recovery. The catch, also known as entry and catch (or glide), is the phase between the entry of the hand and the full extension of the arm, when the opposite hand is coming out of the water (see Fig. 1). The pull can also be subdivided into two phases: the downsweep and the insweep (Callaway et al., 2009; Payton, Bartlett, Baltzopoulos, & Coombs, 1999). The downsweep takes place between the end of the glide, when the hand starts pulling water downwards, and the moment in which the hand is in its most lateral position underwater. Right afterwards, during the insweep, the hand starts pulling water backwards and moves slightly to a medial position, reaching the closest point to the midline of the body. The push (or upsweep) goes from the end of the insweep, when the hand is in the most medial position, until the exit of the hand. Finally, the

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recovery involves the trajectory of the hand from its exit out of the water to the entry, starting a new stroke cycle.

2.1.2 Stroke parameters

The basic spatiotemporal stroke parameters used to assess swimming performance include stroke length (or distance per stroke) and stroke rate (or stroke frequency), the product of which is velocity. Velocity is one of the most critical variables for assessing swimming performance. Stroke length (SL) is the distance covered from the entry of one hand to the entry of the same hand, and the stroke rate (SR) is the number of full stroke cycles completed within one second or minute. Variations in velocity are determined, among other factors (e.g., technique), by increases or decreases in stroke frequency and stroke length (Toussaint & Truijens, 2005). Stroke length has been shown to be the most important parameter related to faster swimming speeds and is calculated based on the formula shown in Equation 2.1.

\[
\text{stroke length (m)} = \frac{\text{swimming velocity (m/s)}}{\text{stroke rate (cycles/sec)}} \tag{2.1}
\]

There is a proportional relationship between velocity and stroke rate, such that stroke rate increases as speed increases. However, a similar relationship does not appear to exist between stroke rate and stroke length. When stroke rate increases the stroke length can vary, and in many cases decreases.
2.1.3 Resistive drag forces

Resistive drag forces cause a diminution in swimming speed by generating longitudinal forces which act in opposition to the forces created by the propulsion of the swimmer’s arms and legs. The amount of drag force depends on many different factors, including swimming technique, velocity, body shape and the anthropometric characteristics of the swimmer.

Equation 2.2 shows how velocity and drag forces are related to each other. An increase in velocity (V) makes it difficult to reduce or maintain the level of drag force (\( F_D \)), particularly because drag force increases with the square of velocity. The amount of body surface area (A) exposed to the flow is critical when attempting to swim at high speeds with a minimal amount of drag. Trying to reduce the area of the body in the transverse plane will help to increase the velocity while keeping the drag force as small as possible.

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

(2.2)

There are two types of hydrodynamic resistive drag: passive and active. The passive drag can be determined by towing a subject through the water without swimming, but this approach does not consider all the drag created by the action of swimming, which is what active drag tries to do. Two swimmers can have a similar passive drag because of their body shape, but the swimmer with better technique will have less active drag and, consequently, less overall drag. There is evidence which shows that passive drag values are lower than active ones and, therefore, active drag is a more important parameter (Kjendlie & Stallman, 2008).
There are three main components of hydrodynamic drag which contribute to the total drag force: friction, form and wave drag (Bixler, Pease, & Fairhurst, 2007). Frictional resistance or ‘skin drag’ occurs due to the interaction between the skin or suit and the water. Decreasing the roughness of the surface exposed to the flow decreases the amount of frictional resistance for a gliding body. The use of caps and body shaving are common strategies that swimmers use to try to reduce friction drag by decreasing the surface roughness. Friction drag is the smallest component of total drag, especially at high swimming velocities, although this drag component should not be disregarded in elite level swimmers (Naemi, Easson, & Sanders, 2010). Quantifying the contribution of the frictional drag to total drag has been extremely difficult but Bixler et al. (2007) found that friction drag represents about 25% of total drag when the swimmer is gliding underwater. Zaïdi, Taïar, Fohanno and Polidori (2008) also found an important contribution of friction drag to the total drag when the swimmer is passively gliding underwater. These authors found that friction drag represents about 20% of total drag. Thus, sports equipment characteristics, shaving and decreasing the amount of immersed body surface area should be considered, since this drag component seems to influence performance especially when gliding underwater after starts and turns. One example is the use of swim suits which are designed to reduce the effect of friction drag.

However, form and wave drag represent the major parts of the total hydrodynamic drag force (Naemi et al., 2010). Form drag is 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. Certain actions like having the head above the water, turning the head to breathe, lowering the legs, having the legs and arms
abducted and body rolling during the streamlined glide on the surface can increase the total drag force mainly due to an increase in the projected area (Naemi et al., 2010).

Wave making resistance or wave drag acts on a body when it moves at the water’s surface. It occurs as a result of the forces associated with the turbulence of the water. Part of the energy from the moving body is used to lift the water against gravity resulting in the formation of waves on the surface. Extending the arms forward increases the body length and thereby reduces the wave drag compared to a posture in which the arms are held against the body. Having the arms at the sides results in 21.5% more drag compared to the streamlined position (i.e., arms forward), which reduces the area of the transverse plane thereby decreasing the braking action of the water (Naemi et al., 2010).

Wave drag also depends on the depth at which the body travels. At a depth of three times the body thickness the wave drag becomes negligible, and has its maximum value when it is submerged just beneath the surface. Recently, Novais et al. (2012) determined that hydrodynamic drag decreases with depth, although beyond a depth of 0.75m the values remain almost constant. Therefore, water depth seems to have a positive effect on reducing hydrodynamic drag during the gliding phase after the start and turns. However, evidence suggests that performing the underwater glide more than 0.75 m below the surface is not beneficial for the swimmer.

2.1.4 Propulsive forces

Drag force was described as a resistive force that acts against the forward displacement of the swimmer. However, the mechanism of drag also serves to create
a propulsive force. Swimmers can accelerate forwards by pushing the limbs backwards against the resistance of the water. This theory is based on Newton’s Third Law of Motion, “To every action there is an equal and opposite reaction”, and it was advocated by coaches in the 1950s and ’60s (Rushall, Sprigings, Holt, & Cappaert, 1994). Nevertheless, it is not the only propulsive mechanism that exists in swimming. Counsilman (1971) proposed that "lift" was the primary mechanism contributing to propulsion whereas drag force was secondary. Lift force is exerted perpendicular to the direction of the drag force. It is caused by differences in the pressure on two sides of an object (such as a swimmer’s hand) moving through a fluid medium, which pushes the object in the direction of the lower pressure (Figure 2). This propulsion theory is based on Bernoulli’s Principle and the Vortex Theory. Bernoulli’s Principle states that fluid pressure is reduced whenever the speed of flow is increased. The difference in pressure between two flows (e.g., above and below the surface of an object) is described as dynamic lift. The most common application of Bernoulli’s Principle is to the shape of an asymmetrical airplane wing. A curved upper surface produces a faster flow of air than does a flat or concave surface on the bottom of the wing, resulting in a pressure differential (this characteristic shape is typically referred to as an airfoil, or hydrofoil). Lift of this nature acts on the body in a direction perpendicular to the path of the object’s movement through the fluid (Maglischo, 2003).

Another theory that has been used to explain how lift forces play a major role in swimming propulsion is the Vortex Theory. Colwin (1992) proposed that the formation of vortices help to maintain a pressure differential between the underside
Figure 2. Components for assessing propulsive forces from a lateral perspective.

and upperside of a swimmer's hand, even when the water flow is turbulent. In Figure 3, Maglischo (2003) represents the mechanism of this theory.

A vortex is defined as a mass of rotating fluid. It begins with the starting vortex on the right side of the figure and a layer of fluid starts to circulate around the object in the opposite direction from the starting vortex, creating the so called bound vortex. The result of these actions is that the pressure differential needed for the production of lift forces will be enhanced between the undersides (+) and upper sides (-) of the hand.

Despite the different theories proposed throughout swimming history, it is generally accepted that drag has a greater contribution than lift to swimming propulsion (Maglischo, 2003). Counsilman (1977) suggested that swimmers moved the hands in S-shaped patterns to get the limbs away from water previously accelerated backwards rather than trying to create a lift force. However, swimmers propel themselves with a combination of lift and drag forces that vary during the phases of the stroke cycle. Figure 4 shows how these forces take place in different phases of the underwater stroke.

**2.1.5 Body roll, breathing and upper limb stroke mechanics**

Body roll is the movement generated by the alternation between left and right arm strokes in freestyle and backstroke. It is an angular motion of the trunk about its long axis and it is usually divided into shoulder and hip roll.

Shoulder roll is measured by the rotation of the shoulder girdle about the longitudinal axis of the body and it has a greater range of motion than hip roll due to
Figure 3. The formation of a vortex (Maglischo, 2003). Reproduced from Swimming fastest. Champaign, IL: Human Kinetics. Reprinted with permission of Human Kinetics and Ernest Maglischo.

the increased mobility of the shoulder girdle compared to the pelvic girdle. When the arm is raised out of the water for recovery, the opposite shoulder rotates toward the recovery arm to allow it to complete this phase. A larger shoulder roll will allow the arm to recover with a smaller horizontal abduction thereby decreasing the radius of its rotation and making the stroke more efficient (Psycharakis & Sanders, 2010).

Hip roll is measured by the rotation of the pelvic girdle about the longitudinal axis of the body. Psycharakis and Sanders (2008) demonstrated that hip and shoulder roll exhibit a different range of motion and reach peak angles at different points in the stroke cycle, finding no consistent pattern.

Table 1 shows mean body roll values from different studies, in which body roll angle has been determined in a number of different ways. Breathing side versus non-breathing side has been the most common classification for body roll when measuring the trunk as a single segment (Barber & Barden, 2014; Beekman, 1988; Liu et al., 1993; Payton et al., 1999). However, some authors have controlled for breathing using different breathing patterns or using a non-breathing trial (Castro, Vilas-Boas, & Guimarães, 2007). Regarding studies that measured shoulder and hip roll individually (Cappaert, Pease, & Troup, 1995; Yanai, 2001), no differentiation between breathing and non-breathing sides has been done so far.

In general, all the studies except one (Beekman, 1988) found that constantly breathing to one side substantially increased body roll to that side. With respect to the studies that measured shoulder and hip roll angle separately (Cappaert et al., 1995; Psycharakis & Sanders, 2008; Sanders & Psycharakis, 2009; Yanai, 2001), they all concluded that shoulder roll was substantially greater than hip roll.
Table 1. Body roll values using breathing and non-breathing classifications. These values exclude those from recreational swimmers, triathletes and injured swimmers.

**Studies that measured body roll**

<table>
<thead>
<tr>
<th></th>
<th>BREATHING SIDE (°)</th>
<th>NON-BREATHING SIDE (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beekman et al, 1988</td>
<td>54</td>
<td>55</td>
</tr>
<tr>
<td>Liu et al. 1993</td>
<td>Not measured</td>
<td>58.75</td>
</tr>
<tr>
<td>Payton et al, 1999</td>
<td>66</td>
<td>57.4</td>
</tr>
<tr>
<td>*Barber &amp; Barden, 2014</td>
<td>63.52</td>
<td>53.7</td>
</tr>
</tbody>
</table>

*Mean values of 4 different conditions: Breathing to preferred side, breathing to non-preferred side, bilateral breathing and not breathing (snorkel)

**Studies that measured body roll regardless of breathing side**

<table>
<thead>
<tr>
<th></th>
<th>BREATHING CONDITION (°)</th>
<th>NON BREATHING CONDITION (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Castro et al, 2006</strong></td>
<td>120</td>
<td>112.15</td>
</tr>
</tbody>
</table>

**Values of total roll angle from right peak body roll to left peak body roll in two different conditions

**Studies that measured shoulder and hip roll**

<table>
<thead>
<tr>
<th></th>
<th>SHOULDER ROLL (°)</th>
<th>HIP ROLL (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cappaert, Pease &amp; Troup, 1995</td>
<td>34</td>
<td>17.8</td>
</tr>
<tr>
<td>Yanai &amp;Hay, 2001</td>
<td>58</td>
<td>36</td>
</tr>
<tr>
<td>Psycharakis &amp; Sanders, 2008</td>
<td>53.35 (non-breathing)</td>
<td>25.15</td>
</tr>
<tr>
<td>***Sanders &amp; Psycharakis, 2009</td>
<td>103.9 (non-breathing)</td>
<td>46.8</td>
</tr>
</tbody>
</table>

***Values of total roll from right peak body roll to left peak body roll
There is also evidence to suggest that swimming speed has an effect on body roll. Castro et al. (2007) demonstrated that as velocity increases, body roll decreases. Swimmers in their study significantly decreased body roll as self-determined velocity increased from slow to moderate to fast. Psycharakis and Sanders (2008) also observed that faster swimmers had significantly less shoulder roll than slower swimmers in a maximal 200m freestyle 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. Psycharakis 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. In general, research suggests that an inverse relationship exists between body roll angle and velocity.

Changes in body roll are also closely related to handpath during the stroke and while breathing. Liu et al. (1993) concluded that the medial-lateral motions of the hand observed during the stroke were not only caused by the motions of the hand relative to the trunk, but also to the rolling action of the swimmer’s trunk. Regarding breathing, swimmers roll their shoulders and hips to the breathing side significantly more in the breathing than in the non-breathing situation (Psycharakis & McCabe, 2011), probably to facilitate the turning of the head to take a breath (Payton et al., 1999; Yanai, 2001). Therefore, we can suggest that breathing also has an effect on the stroke pattern. In fact, Vezos et al. (2007) noticed that the displacement of the hand in the transverse plane during the downsweep phase was significantly increased by breathing. At the same time, the hand’s lateral displacement during the push phase
decreased significantly from the end of the most medial position of the hand in the transverse plane to hand exit. However, body roll was not measured, so its relationship with the previous variables was not analyzed.

The following description explores how the upper limb behaves during the freestyle stroke, paying special attention to the shoulder joint (Fig. 5). During the hand entry and catch phase of the stroke (A-right), the shoulder is in external rotation and flexion, and the body roll begins. In the pull phase (B-right), the shoulder is at 90° of abduction and neutral internal-external rotation. Finally, in the push phase (C-right) the shoulder is internally rotated and fully adducted and the body has returned to a neutral position of longitudinal rotation (Richardson et al., 1980). The recovery phase can be divided into three sub-phases to describe the shoulder position: elbow lift, mid-recovery and hand entry. During the elbow lift (A-left) the shoulder begins to abduct and externally rotate. Here the body begins to roll in the opposite direction from the previous phase. In the mid-recovery phase (B-left) the shoulder is abducted to 90° and externally rotated beyond the neutral position. The body roll reaches its maximum around 40-60° and breathing can occur by turning the head to this side. The hand entry (C-left) happens with the shoulder externally rotated and maximally abducted, and the body returns to a neutral position, zero degrees of longitudinal roll (Richardson et al., 1980).

Given the difficulty of quantifying the complex motion of the upper limb, very few studies have described the upper limb kinematics of freestyle swimming (see Fig. 6), but in the available research, the following variables have been identified as being important (Payton et al., 1999):
**Figure 5.** Shoulder mechanics in freestyle swimming. Reproduced from The shoulder in competitive swimming, Richardson, A. B., Jobe, F. W., & Collins, H. R., American Journal of Sports Medicine, Copyright © (1980, SAGE Publications). Reprinted with permission of SAGE Publications.

**Figure 6.** Upper limb kinematics. Adapted from Upper extremity kinematics and body roll during preferred-side breathing and breath-holding front crawl swimming, Payton, C. J., Bartlett, R. M., Baltzopoulos, V., & Coombs, R., Journal of Sports Sciences, Copyright © (1999, Taylor & Francis). Reprinted with permission of Taylor & Francis Ltd.
— Shoulder flexion angle (A): the angle between the shoulder-to-elbow position vector and the x-axis, when projected onto the sagittal plane.

— Shoulder roll angle (B): the angle between a line connecting the two shoulder joints (the shoulder axis) and the horizontal (x-z) plane

— Shoulder horizontal adduction angle (B): the angle between the shoulder-to-elbow position vector and the shoulder axis.

— Shoulder internal-external rotation angle (C): the angle between the forearm position and the y-axis.

— Elbow flexion angle (B): the angle between the upper arm and lower arm segments.

Some studies also consider the pronation-supination of the elbow, and the flexion-extension and radial-ulnar deviation of the wrist (Magalhaes, 2014) and variables that describe the handpath during the stroke (Fig. 7): i.e., displacement of the hand during the pull, pull width, pull depth and pull length (Vezos et al., 2007).
2.2 Swimmer’s Shoulder

Swimmer’s shoulder was first described by Kennedy & Hawkins (1974) as the painful state that occurs due to the repetitive impingement of the shoulder. There is no single clinical diagnosis, but it is described as a syndrome which is characterized by subacromial impingement of soft tissue structures against the coracoacromial arch. These structures include the contents of the so-called subacromial outlet: the ‘rotator cuff’ of muscles and tendons that surround the shoulder joint and the subacromial bursa that overlies it, as well as the biceps tendon, which arches over the humerus, deep to the rotator cuff and within the shoulder joint itself (Hanchard, Lenza, Handoll, & Takwoingi, 2013). The supraspinatus tendon is the most commonly affected structure (Penny & Smith, 1980), but several secondary pathologies are usually associated with this impingement. These include subacromial-subdeltoid bursitis (inflammation of the subacromial portion of the bursa, the subdeltoid portion, or both), tendinopathy or tears affecting the rotator cuff or the long head of the biceps tendon and glenoid labral damage (Hanchard et al., 2013).

Competitive swimmers can train between 10,000 and 14,000 meters a day, for six or seven days per week (distances of 50-60 km per week are not uncommon). This is equivalent to a minimum of 16,000 revolutions of each shoulder per week (Hibberd, Oyama, Spang, Prentice, & Myers, 2012). Nearly 90% of the power that propels the swimmer forward comes from the upper limbs (Heinlein & Cosgarea, 2010). This explains the high number of injuries in the shoulders of swimmers. In fact, the most common musculo-skeletal problem for competitive swimmers is shoulder pain (Wanivenhaus et al., 2012). The incidence of shoulder pain among
swimmers has been reported in 47% of 13 to 14 year-olds, 66% of 15 to 16 year-olds, and 73% of elite college swimmers (Davies et al., 2008).

Neer & Welsh (1977) described four phases of swimmer’s shoulder: Phase I, pain only after heavy workouts; Phase II, pain (not disabling) during and after workouts; Phase III, disabling pain during and after workouts that interferes with the swimmer’s performance; and Phase IV, shoulder pain that prevents competitive swimming. In the last phase, pain at rest and sleep disturbances are often seen. The classification can be useful in the clinical evaluation and as a guideline during rehabilitation.

2.2.1 Etiology

Many factors have been identified as potential contributors to the syndrome known as Swimmer’s shoulder. Extrinsic factors, such as sudden increases in the training volume, the excessive use of hand paddles and technical errors seem to be important (Bak, 2010). Improper changes in training frequency, duration or intensity can lead to early fatigue, abnormal loading of tissues, repetitive microtrauma and inadequate time for tissue recovery. The excessive use of training devices like paddles or kickboards creates an overload of soft tissues and the activation of inflammatory injury responses (Davies et al., 2008). With respect to the biomechanics of the stroke, breathing, stroke technique and body roll are all believed to be important factors. However, there is no agreement in the available research in this area, as will be shown below in the pathomechanics section (see 2.2.2).

Regarding the intrinsic factors involved in swimmer’s shoulder, the following characteristics play an important role: capsular abnormalities, muscle weakness and
imbalances, deficits in neuromuscular control and impaired posture. With respect to capsular abnormalities, joint hyperlaxity (i.e., excessive looseness and motion of the glenohumeral joint) is one of the most common problems among swimmers. This can lead to multidirectional instability, which increases the probability of shoulder pain (McMaster, Roberts, & Stoddard, 1998). Posterior capsule tightness (hypomobility) and anterior inferior hypermobility of the glenohumeral (GH) joint can also cause anterior translation of the humeral head, increasing the risk of impingement (Davies et al., 2008). Nevertheless, it is important to note that hypomobility of the GH joint has also been correlated with shoulder pain, suggesting that an intermediate range of motion is ideal for injury prevention (Walker, Gabbe, Wajswelner, Blanch, & Bennell, 2012).

With respect to muscle weakness and activation, dynamic electromyography (EMG) has shown that during the early pull-through phase of the stroke there is a significant decrease in the activity of the upper trapezius, rhomboids and serratus anterior, and a significant increase in subscapularis activity in swimmers with painful shoulders compared to asymptomatic swimmers (Pink et al., 1993; Scovazzo, Browne, Pink, Jobe, & Kerrigan, 1991). The function of these muscles is to stabilize the scapulothoracic joint. Therefore, the insufficient activation of these muscles contributes to scapular dynamics that may deviate from normal stabilisation. For instance, a shortened pectoralis minor and weak scapulothoracic muscles can cause an anterior tilt of the scapula, decreasing the subacromial space and increasing the risk of impingement (Kluemper, Uhl, & Hazelrigg, 2006). In terms of muscle imbalances, Batalha, Marmeireira, Garrido & Silva (2015) found that during a swimming training macrocycle, swimmers developed more muscle strength in the
internal rotators, contributing to a greater muscle imbalance of the rotator cuff. The authors suggested that this could be a potential mechanism for injury. However, a limitation of the study was that the external rotators were only measured concentrically. External rotators work eccentrically during the underwater phases of the stroke cycle to provide stability to the GH joint, so future research should measure the tolerance to fatigue of these muscles during eccentric work.

Concerning deficits in neuromuscular control, a motor coordination problem known as scapular dyskinesis is a common term found in the literature regarding shoulder pathology (Kibler et al., 2013). It is described as an inadequate scapular stabilization that may result in abnormal loading of the GH joint and surrounding soft tissues. Wadsworth and Bullock-Saxton (1997) suggested that the timing of muscle activity during freestyle is as important as the level of activation. They found that injured swimmers had significant variations on the involved side for the upper and lower trapezius and serratus anterior. They suggested that fatigue of the serratus anterior is probably one of the primary problems leading to an uncoordinated pattern of scapular motion. This prevents the protraction and upward rotation of the scapula during hand entry, increasing the risk of impingement (Davies et al., 2008). However, despite the importance that scapular motion has for the normal movement of the shoulder complex, it is unknown to what degree scapular dyskinesis and shoulder pain are related. Kibler et al. (2013) stated that it remains unclear if scapular dyskinesis is the cause of pain or part of the outcome. For instance, Tate et al. (2012) did not find differences in scapular motion between healthy and injured female swimmers. In addition, many methods to evaluate scapular dyskinesis show low sensitivity and specificity (i.e., they fail to diagnose dyskinesis when it exists, and
they diagnose it when it does not exist), suggesting that it is difficult to measure objectively (Wright, Wassinger, Frank, Michener, & Hegedus, 2013).

Finally, some authors state that a correlation exists between posture and shoulder pain (Davies et al., 2008). They suggest that adaptive postural changes produce modifications in the normal physiologic length-tension relationships of the muscles, changing the biomechanics of the joint. For example, an increased thoracic kyphosis along with a shortened pectoralis minor would cause the scapulae to work with an increased anterior tilt, reducing the subacromial space and facilitating the impingement. However, recent trials suggest that acromiohumeral distance may not be that relevant, as there is no correlation between this variable and shoulder pain and function (Navarro-Ledesma et al., 2017), and the variation when performing abductions with scapular retraction has minimal influence on acromiohumeral distance (Harput et al., 2018).

2.2.2 Pathomechanics

As mentioned previously, technique plays an important role in injury prevention and certain swimming mechanics can be harmful for the shoulder, especially if the technical errors are not modified in the first stages of the injury (Richardson et al., 1980). Richardson et al. (1980) found that seventy-five per cent of the swimmers with shoulder pain considered freestyle or butterfly to be their best stroke, with freestyle being the most commonly used stroke during practice. In the freestyle stroke pattern, Bak (1996) described three situations that could damage the anteroinferior capsulolabral complex and the rotator-cuff (Fig. 8).
Figure 8. Potentially harmful upper limb movements during the stroke (Bak, 1996). A: right arm. B: right arm C: left arm. Reproduced from Nontraumatic glenohumeral instability and coracoacromial impingement in swimmers, Bak, K., Scandinavian Journal of Medicine & Science in Sports, Copyright © (2007, John Wiley and Sons) Reprinted with permission from John Wiley and Sons.
These risk situations during swimming are theoretical, based on upper limb movements that have shown to be harmful in laboratory setups: (A) The early pull-through, when the shoulder is in maximum abduction/flexion and external rotation. In this position the body’s inertia has to be overcome, putting (in theory) the load to its highest point during the stroke cycle. According to Turkel et al. (1981), this repetitive movement weakens the capsuloligamentous complex, in particular the inferior GH ligament. They used cadavers to explore how different movements of the upper limb affected the capsuloligamentous complex of the GH joint. This position of the arm during the early pull-through phase causes the humeral head to impact against the inferior GH ligament, creating hyperlaxity through repetitive stress.

(B) In the last part of the pull-through phase a powerful adduction and internal rotation movement is generated, potentially compressing the rotator cuff and compromising its vascularization, which increases the risk of tendonitis (Rathbun & Macnab, 1970).

(C) The remaining injury provoking situation occurs during recovery when the arm is repetitively abducted and externally rotated causing stress of the long biceps or the supraspinatus tendons on the coracoacromial arch (Richardson et al., 1980).

Out of these three risk situations, seventy-five percent of the swimmers indicated that their pain came during both the pull-through and recovery phases, especially at or just after hand entry, while the shoulder is fully abducted (Richardson et al., 1980).

However, the position of the shoulder and the upper limb in the stroke pattern can vary depending on other factors like body roll and breathing. Liu et al. (1993) reported a mean value of 60.8° for body roll to the non-breathing side (body roll to
the breathing side was not calculated) and stated that the mean contribution of body roll to hand path was 52.1% and was nearly equal to the contribution of the mediolateral motions of the arm (shoulder and/or elbow). Some authors suggest that an increased body roll increases the reach of the arm entering the water and subsequently increases stroke length. At the same time this would allow a greater protraction of the scapula, permitting the arm to be pulled back in line with the shoulder, thereby reducing lateral shoulder torque and reducing the stress placed on the shoulder (Weldon & Richardson, 2001). Penny et al. (1980) also suggested that encouraging body roll and alternate breathing would reduce impingement of the supraspinatus and long biceps tendon against the coracoacromial arch. This would reduce the stress placed on the shoulder both for the underwater pull, as mentioned above, and also during arm recovery by reducing the amount of horizontal abduction and, therefore, the impingement risk.

No evidence exists in the current literature with respect to how all of these variations in stroke mechanics affect shoulder pain, but Richardson et al. (1980) suggested that research into the technical differences between those subjects with shoulder pain and those without is necessary to shed light on which technique elements should receive attention to prevent shoulder pain. They also hypothesized that based on the evaluation of slow motion underwater video analysis, body roll could be a significant determinant of pain in freestyle swimming. Davies et al. (2008) suggested that swimmers who consistently turn their heads to the same side to breathe are risking shoulder pain in the opposite shoulder. They argued that this causes the swimmer to work harder to support forward movement with the head turned to the side, which leads to overuse conditions. However, they also stated that
this hypothesis has not been demonstrated in the literature and that it remains controversial.

2.2.3 Bilateral asymmetry

Most of the available research shows a greater incidence of unilateral compared to bilateral shoulder pain. Between 59 and 85 per cent of the swimmers with shoulder pain have unilateral pain (Bak & Fauno, 1997; Richardson et al., 1980; Sein et al., 2010), leaving a small percentage of swimmers with bilateral pain. Some authors have attempted to explain these findings by relating it to the asymmetry that can occur during swimming. One of the contributors to the asymmetry of the stroke in front crawl arises from the natural tendency to favor one side when breathing (Sanders et al., 2011; Seifert et al., 2005), but no agreement can be found in terms of how breathing and pain are related to each other. Richardson et al. (1980) found that 66% of swimmers presented pain on the breathing side while other studies (Bak & Fauno, 1997) found no correlation between breathing side and pain and hypothesized that breathing to one side increases the risk of impingement on the contralateral shoulder. They explained that breathing to one side is often associated with an insufficient body roll to the opposite side, requiring additional horizontal abduction of the shoulder complex and, therefore, an increase in stress on the anterior side of the joint during the recovery phase.

Differences in body roll between breathing and non-breathing conditions have also been investigated. The results have been inconsistent across studies although there is a tendency to suggest that swimmers roll more to the breathing side. Beekman (1988) reported significant differences between breathing and non-
breathing conditions for a group with shoulder injury (breathing body roll: 60º; non-breathing body roll: 48º), but no differences for an injury-free group (breathing body roll: 54º; non-breathing body roll: 55º). In contrast, for a small sample (n=6) of healthy swimmers, Payton et al. (1999) found that they rolled on average 9º more during the breathing (66º) than the non-breathing trial (57º). Castro et al. (2007) reported that most of their swimmers rolled more when breathing (with the exception of long-distance swimmers when tested at low self-selected intensities), but there were no differences between breathing and non-breathing conditions for the triathletes. One explanation for the discrepancies across studies could be that body roll patterns of injured swimmers, as suggested by Beekman (1988), were not as consistent as those of the healthy swimmers. Another explanation could be the large range of swimming speeds. Castro et al. (Castro et al., 2007) demonstrated that body roll in swimmers decreased when speed increased.

Magalhaes (2014) also reported stroke asymmetries in swimmers when looking at the patterns of movements between left and right limbs. They reported bilateral asymmetries in shoulder flexion-extension, abduction-adduction and internal-external rotation. However, comparing both sides was not the purpose of the study and, therefore, limited information was given in this area. The inconsistencies found among injured swimmers supports the idea that there may be a relationship between asymmetry and injury (Beekman, 1988; Pscharakis & Sanders, 2010). However, no strong evidence can be found to unequivocally support a relationship between bilateral asymmetry and unilateral shoulder pain. Some authors conclude that many questions still remain unanswered with respect to how asymmetries affect performance and injury risk and how amelioration of asymmetries can be achieved.
(Sanders et al., 2011). Although such asymmetries are not clearly linked to performance, it has been suggested that asymmetries and movement variability could be functional for the purpose of reducing injury risk (Davids, Glazier, Araujo, & Bartlett, 2003). Thus, the study of the links between body roll and injury prevention/treatment should include consideration of body roll side dominance, asymmetries and variability. Psycharakis & Sanders (2010) suggested that obtaining a more complete picture of the links between shoulder roll and the prevention/treatment of overuse shoulder injuries is required. They explained that research should be expanded to include swimmers with a range of abilities from both sexes, and take into account other variables that could improve the understanding of the potential links between body roll and injury prevention and treatment.

### 2.2.4 Treatment and prevention

Gaunt et al. (2012) carried out a systematic review on rehabilitation and treatment of shoulder injuries in swimming. Based on those articles, they described four phases for conservative treatment in swimmers with secondary shoulder impingement (i.e., caused by capsular abnormalities or hyperlaxity). Phase I aims to establish a firm scapular base from which to strengthen the rotator cuff in a neutral position. Phase II uses strengthening exercises in the 0–90° flexion-abduction range, before moving to overhead exercises in Phase III, where functional training is introduced. Phase IV sees the swimmers return to a full training program, aiming to reach their pre-injury ability. It was also recommended that any strengthening program should mirror the extreme repetition and muscular endurance required in swimming.
Prior to Phase I, and depending on the severity of the injury, pain and inflammation should be addressed. Eliminating all the potential extrinsic risk factors reviewed in the etiology section is essential. Rest, avoidance of painful movements and nonsteroidal anti-inflammatory drugs should take place prior to initiating the strengthening process along with manual therapy that aims to reduce muscle and capsular shortenings (Davies et al., 2008).

Subsequently, Phase I should include scapulothoracic muscle strength, endurance and motor control. Moseley, Jobe, Pink, Perry & Tibone (1992) identified four important exercises for scapulothoracic muscles, measuring their activation with EMG (Fig. 9). These include scaption (flexion in the scapular plane) with the thumb up for the upper trapezius (A); push-ups with a plus (i.e., with scapular protraction) for serratus anterior (B); press-ups for lower trapezius, latissimus dorsi and teres major (C), and scapular retraction for middle trapezius and rhomboids (D).

Within Phase II, including exercises for muscles surrounding the GH joint and rotator cuff strengthening is important. Townsend, Jobe, Pink & Perry (1991) identified four important exercises for glenohumeral muscles, measuring their activation with EMG (Fig. 9). These include scaption with the thumb down for supraspinatus (A); press-ups for the lower fibers of subscapularis, lower fibers of infraspinatus and teres minor (C); glenohumeral flexion for anterior deltidoid and coracobrachialis (E), and external rotation with horizontal abduction (F).
Figure 9. Exercises for scapulothoracic and glenohumeral muscle strengthening.

Adapted from EMG analysis of the scapular muscles during a shoulder rehabilitation program, Moseley, J. B., Jobe, F. W., Pink, M., Perry, J., & Tibone, J., American Journal of Sports Medicine, Copyright © (1992, SAGE Publications). Reprinted with permission of SAGE Publications.
However, Timmons, Ericksen, Yesilyaprak & Michener (2015) recently showed that scaption should be carried out with the thumb up as represented in Figure 9 (A). Executing the exercise with the thumb down was associated with more pain and scapular positions that have been reported to decrease the subacromial space. Regarding the strengthening of the rotator cuff using internal and external rotation exercises, Phase II should include rotations in 30 degrees of scaption as described by Davies and Dickoff-Hoffman (1993). This position prevents the wringing-out effect of the supraspinatus, protects the anterior-inferior capsule and involves a functional arc of motion of the shoulder (Davies et al., 2008). When moving to Phase III, these exercises should progress to overhead positions aiming to replicate the front crawl position. These rotation exercises should pay special attention to external rotators if rotator cuff strength imbalances are identified in the swimmer (Batalha et al., 2015).

Finally, Phase IV includes returning to the full-training program. It is important to schedule a progressive return to swimming, including dryland and pool training. The use of hand paddles should be discontinued and the use of a kickboard minimized. Weldon et al. (2001) recommended decreasing the emphasis on anterior capsule stretching and focusing more on posterior capsule stretching. They also recommend increasing rotator cuff strengthening in this phase, with an emphasis on external rotation. Davies et al. (2008) suggest the importance of using bilateral breathing to increase body roll. They also suggest that the following criteria should be met before returning to a full-training program:

— Possessing a full range of motion and adequate upward scapular rotation.
— Tolerating rotator cuff strengthening exercises, resisted movements into provocative overhead positions and scapulothoracic strengthening exercises with no pain.

— Being able to swim 500 yards at a warm-up intensity without symptoms.

The above described conservative treatment is a general procedure for swimmer’s shoulder, but physiotherapists should individualize it based on the specific shoulder disorder of the swimmer and their progression. Sprinters and long-distance swimmers also require different rehabilitation programs (Gaunt & Maffulli, 2012). Sprinters should perform a smaller number of repetitions with a greater weight to build and maintain explosive power. Long-distance swimmers conversely should perform a greater number of repetitions with less resistance.

Medical treatment for shoulder pain should take the form of nonsteroidal anti-inflammatory drugs as a first-line treatment, followed by a 1 ml betamethasone (6 mg/ml) subacromial injection in 9 ml of 1% lidocaine if pain is constant and rehabilitation is hindered (Gaunt & Maffulli, 2012). Surgical treatment is only recommended as a last resort, and should be carried out between 3 and 6 months after the onset of pain if there is no improvement with conservative or medical measures (Brushøj, Bak, Johannsen, & Faunø, 2007). Different surgical techniques can be used depending on the underlying cause of pain. When impingement is the cause of pain, the recommended procedure is an arthroscopy to decompress the subacromial space (Reynolds, Bramhall, Scarpinato, & Andrews, 2009). These can include acromioplasty, debridement, release of the coracoacromial ligament and bursectomy.
The acromioplasty involves removing part of the anterior acromion, to
decrease the impact of rotator cuff or long head of the biceps tendons against this
structure. Debridement consists of removing loose fragments of tendon, thickened
bursa, and other debris from around the shoulder joint that could be compromising
the subacromial space. Release of the coracromial ligament is carried out by partial or
total resection. When partial resection is performed, only the anterior band of the
ligament is removed. This increases the distance between the humeral head and the
coracromial arch, reducing the risk of impingement (Edwards, Bell, & Bigliani,
2008). Finally, a bursectomy involves the resection of the subacromial bursa.
Sometimes, its inflammation can compromise the subacromial space and be a cause
of pain (Edwards et al., 2008).

Donigan and Wolf (2011) carried out a systematic review in which they found
no significant differences in results between acromioplasty and bursectomy
suggesting that acromioplasty might not always be necessary. Between 50 and 81 per
cent of athletes undergoing surgery have good results, with only two thirds of them
being able to return to overhead sports (Edwards et al., 2008). Brushoj et al. (2007)
reported on surgeries with 16 swimmers. The most common operative procedure was
debridement, followed by partial release of the coraco-acromial ligament and
bursectomy. Nine swimmers (56%) returned to their preinjury level, seven (44%)
without shoulder pain, and two (12%) with some shoulder pain. Seven (44%) never
returned to competitive swimming, six of these (38%) due to shoulder pain. The
median time to return to swimming activity at the preinjury level was 4 months
(Gaunt & Maffulli, 2012).
Even though surgery is recommended when conservative treatment has failed, recent reviews (Gebremariam, Hay, Koes, & Huisstede, 2011; Tashjian, 2013) have concluded that there is no evidence that surgical treatment for subacromial impingement syndrome is superior to conservative treatment or that any particular surgical technique is superior to another. In addition, two recent surgical trials suggest that difference between patients undergoing surgery and those receiving no treatment might be due to a placebo effect or to post-operative physiotherapy (Beard et al., 2018; Paavola et al., 2018). Because of a reduced risk of complications, conservative treatment is preferred. However, if there are rotator cuff or labral tears associated with the impingement syndrome and the athlete’s objective is to return to the same performance level, these pathologies will need to be surgically addressed (Anbari, Verma, Cohen, & Romeo, 2009). When choosing to undergo surgery, arthroscopy may be preferred because of the less invasive character of the procedure.

In summary, rehabilitation of swimmers’ shoulder should take the form of clinical assessment, technique assessment (along with correction) and promotion of stability between muscles involved in the swimming stroke. If rehabilitation is not successful, medical treatment and surgical procedures are available, even though there is no evidence to suggest they are better for impingement syndromes with no rotator cuff or labral tears. Most studies agree with starting conservative and medical treatment first, and using surgery as a last resort (Gaunt & Maffulli, 2012).

With respect to prevention, swimmers and coaches should be well educated on topics such as early injury prevention and detection, together with a multidisciplinary approach including sports therapists and, if available, a team doctor.
Musculoskeletal injuries in this population usually result from cumulative and repetitive trauma. Careful monitoring of training volume, intensity, and duration by coaches and physicians will minimize overuse injuries and identify athletes at risk (Wanivenhaus et al., 2012). Abdominal and scapular muscle strengthening should be emphasized in the dryland training program. An endurance training and strengthening program for the shoulder and periscapular muscles, with emphasis placed on the serratus anterior, rhomboids, lower trapezius, and external rotators may help prevent injuries (Wanivenhaus et al., 2012). All the exercises described for the conservative treatment of swimmer’s shoulder are beneficial for the development of these muscles. Tate et al. (2012) found that female swimmers with shoulder pain had decreased core endurance, so including a core strengthening program may also be beneficial. They also found that swimmers with pain had pectoralis minor tightness, suggesting that stretching this muscle should be part of a prevention plan. Individual swimmers should be evaluated to determine strength, endurance and flexibility deficits. A comprehensive program can be performed with minimal equipment like elastic bands.

Regarding stroke biomechanics, many authors suggest that enhancing body roll would prevent some of the aforementioned harmful shoulder movements to occur during the stroke (Davies et al., 2008; Penny & Smith, 1980; Richardson et al., 1980). However, the evidence in this regard is vague and no experimental studies exist in which the relationship between body roll and shoulder pain has been analyzed. Davies et al. (2008) also suggest that the so called “dropped elbow” (i.e., touching the water surface with the elbow prior to the hand in the entry phase and lowering the elbow during the end of the catch phase) should be avoided as it increases the
probability of causing subacromial impingement. This recommendation is also based on a theoretical mechanism, so no clear evidence-based information is available to create prevention guidelines regarding stroke technique.

2.3 Biomechanical analysis

Using the latest technology to enhance performance is important, as it can be a source of detailed information about the movement in question, and therefore an aid to improving swimming technique and avoiding harmful movements of the upper limb. A swimmer’s potential can be maximized with a better understanding of swimming biomechanics, which is provided by the analysis of the stroke in the water (Callaway et al., 2009). Systematic biomechanical analysis identifies technical errors and monitors performance progress of technique, with the goal of providing individuals with a more efficient stroke. In this section, different methods for biomechanical analysis will be described.

2.3.1 Video analysis

Video recording has been widely used by the swimming research community as one of the best approaches for motion measurement (Psycharakis & McCabe, 2011; Vezos et al., 2007). It is performed by using above or below water camcorders that record a raw video sequence, from which specific points of interest are tracked using a variety of software packages. The points tracked are anatomical landmarks that provide a basis for the kinematic modeling of the body, and typically include the wrists, elbows and shoulders for the upper limbs, and the hips, knees, and ankles for the lower limbs (Ohgi, Yuji, 2002; Pansiot et al., 2010).
There are two different ways to implement videocamera analysis: the marker approach, which is the most common one, and the markerless approach. Motion analysis can occur in either 2D or 3D, depending on the equipment available (e.g., the number of cameras) and the variables that need to be analyzed. For the marker approach, markers are located at key positions on the swimmer’s body, such as the wrist. The coordinates are then manually digitized and extracted. For the 3D recordings, this procedure is carried out using the Direct Linear Transformation (DLT) method. The DLT is an established algorithm that allows multiple images captured by different cameras to be extracted on a frame-by-frame basis. This allows a composite 3D representation of position versus time to be constructed with minimum error, as well as the body segment paths during an entire stroke (Callaway et al., 2009; Ohgi, 2002). By creating a full body-segment model composed of nineteen body landmarks, Psycharakis and Sanders (2008) used a marker fixed on the swimmer’s center of mass to measure shoulder and hip roll changes during freestyle swimming.

While the DLT approach has been successfully employed as an analytical tool in many sport disciplines, its application to assessment of swimming performance is limited by the various difficulties associated with using a camera to obtain images in water. These include the turbulence affecting the view of anatomical points of interest, occlusion of markers leading to a loss of continuity in the data required for successful application of the DLT algorithm, and refraction of light in water that causes errors in reconstruction of trajectory data when using the DLT algorithm (Callaway et al., 2009). Kjendlie and Olstad (2012) tested a system with 6 cameras and reported an increase of 7% to 10% in the passive drag due to the resistance
exerted by the 24 markers attached to the swimmer. This suggests that the use of markers of non-negligible volume in the water is questionable because it might negatively affect the swimmer’s performance by increasing drag. A possible approach to avoid this consists of replacing the spherical markers with bi-adhesives placed on the swimsuit, or with markers drawn on the swimmer’s skin (Ceccon et al., 2013).

The markerless system has been suggested as an alternative method in the last few years for a number of different sports. With markerless technology (which has only recently become available), it is possible to automatically estimate the position of body segments from conventional cameras, without the need to draw or attach markers to the subject’s skin. The background subtraction step is the most common approach, in which the room’s wall and floor are covered with blue or green panels and then the background is digitally removed to isolate only the exercising subject for the digitizing process (Corazza, Gambaretto, Mundermann, & Andriacchi, 2010; Magalhaes, 2014). Subsequently, the chosen body landmarks are tracked and digitized without the need to use markers. However, this method has not been used for biomechanical analysis in swimming. Marker tracking is still the most accurate and comprehensive method and it provides relevant data to coaches and athletes (Callaway et al., 2009; Magalhaes et al., 2015).

Many limitations of the video analysis approach have been described above. However, despite the limitations of video-based analysis, this technique has formed the basis on which the understanding of swimming performance has been built over the last three decades (Callaway et al., 2009). Nevertheless, new alternative methods
are being explored. They are less time consuming and easier to use on a daily basis for coaches and health professionals. They will be described in the following section.

### 2.3.2 Inertial Measurement Units

In addition to the limitations mentioned previously, video analysis can only provide information for approximately 1-2 strokes per trial due to the need to use fixed cameras that calibrate a small recording zone. Another limitation is the time-intensive process of digitization and data processing required to extract useful data (Magalhaes, 2014). A recent development in swimming biomechanics involves the use of body-fixed sensors such as Inertial Measurement Units (IMU). The advantage of using this approach is that it provides the ability to record continuous data for the entire length of the pool and to continue doing so for multiple lengths. This provides information about intra-trial variations in stroke mechanics without interruptions to the natural rhythm of the stroke cycle that can occur when a swimmer is aware of a recording zone.

IMUs are electronic devices comprised of an accelerometer, a gyroscope and a magnetometer, which measure the tri-axial linear acceleration, the tri-axial angular velocity and the tri-axial components of the earth’s magnetic field, respectively (Callaway et al., 2009). With proper calibration, the axes of this local coordinate system are typically aligned with the outer casing of the sensor. Some commercially available devices incorporate algorithms that provide estimates of the sensor’s orientation with respect to a global (i.e., fixed) coordinate system (Seel, Raisch, & Schauer, 2014). Depending on the biomechanical analysis to be implemented, the
individual components of the IMU can be used separately to understand the information that each offers to the biomechanical analysis of swimming.

Several studies have shown that accelerometer data can be used for the purpose of stroke phase discrimination (Ohgi, Y., Yasumura, Ichikawa, & Miyaji, 2000; Siirtola, Laurinen, Röning, & Kinnunen, 2011). For example, Ohgi et al. (2000) were the first to identify, in a case study, the different phases of the stroke cycle using an accelerometer attached to a swimmer’s wrist. In freestyle, impact acceleration occurs at the moment of hand entry because of the collision between the swimmer’s hand and the water surface. This impact appears in the X-axis and Z-axis accelerations (Fig.10). For the X-axis, this event appears as a sharp negative peak (I). This study demonstrated that the following stroke phases could be determined by the tri-axial accelerometer: the entry and stretch or catch (I), downsweep (II) and insweep (III) or pull, and upsweep and recovery (IV). After entry, the Y axis acceleration decreases to 0 m/s², which corresponds to the end of the stretch phase. After the Y-axis acceleration reaches 0 m/s², the X-axis increases steeply to reach a local maximum. During this phase, the swimmer’s hand moves outward and downward. This corresponds to the downsweep phase. At the time of the X-axis local maximum, the swimmer’s hand is at its deepest position. Then the swimmer’s hand moves inward between the X-axis local maximum and the X and Y-axis local minimums. This corresponds to the insweep phase. After the insweep phase, the Y-axis acceleration increases steeply, which corresponds to the upsweep phase.
Figure 10. Accelerometer based stroke phase discrimination. Reproduced from Microcomputer-based acceleration sensor device for sports biomechanics, Y. Ohgi, Sensors, Copyright © (2002 IEEE). Reprinted with permission of IEEE.
This study demonstrated that a number of important stroke parameter variables, that are difficult to measure using video (because of the time required to digitize and conduct a frame-by-frame analysis), can be easily measured with an accelerometer. However, the study was carried out using one swimmer and only analyzed a single stroke, freestyle. Therefore, it is not possible to state that this method is valid for every swimmer and for every stroke. In addition, the variations in acceleration on the different axes are specific to this study and could vary for other studies depending on the orientation of the sensor.

Siirtola (2011) also reported on stroke type identification and turn discrimination testing 11 subjects, and obtained good results, suggesting that accelerometers can be used as an accurate tool for this purpose. Other studies have shown that accelerometers can be used to identify stroke parameters such as stroke asymmetry and timing (Stamm, James, Hagem, & Thiel, 2012) and body roll angle (Bächlin & Tröster, 2012; Barber & Barden, 2014).

The second component of an IMU is the rate gyroscope, which provides information about angular velocity. Estimates of the 3D orientation of a rigid body can be calculated by integrating the tri-axial signals obtained from it. This will be explained in the next section. However, problems can occur using this approach due to the low-frequency bias drift. Basically, this means that small errors in the measured angular velocity will be compounded during the integration process resulting in increased errors in the determination of angular position. It is important to note that a relatively small offset (or bias) in the gyroscope signal will give rise to large integration errors. This problem can be reduced using a fusion approach, which
involves a combination of gyroscope, accelerometer and magnetometer signals (Magalhaes, 2014). Even though some limitations still exist, sensor fusion is the best technique when the aim is to minimize gyro bias drift error.

The third component of the IMU, the magnetometer, plays an important role in estimating the heading (i.e., the directional bearing) of the IMU. Magnetometers have significant limitations for swimming biomechanical analysis, as the presence of magnetic disturbances (induced by ferromagnetic materials) may limit the accuracy of the orientation estimates, being especially critical within indoor environments (Seel et al., 2014).

Ideally, an orientation filter should be capable of dealing with the problems regarding both the gyro biases and magnetic sensors. The task of an orientation filter is to compute a single estimate of orientation through the optimal fusion of gyroscope, accelerometer and magnetometer measurements. Most of the IMUs available now use an orientation filter proposed by Kalman (1960) which has shown to be accurate and facilitates the extraction of the angular position (Luinge & Veltink, 2005; Magalhaes, 2014).

Despite all the advantages sensors have to offer, several limitations exist with respect to some of the variables they can measure. For example, the process used to obtain information about joint kinematics is still time consuming, as has been described by Magalhaes (2014), and has not been validated by comparison to the standard video-based approach. Another important variable that has not been measured with sensors is stroke length. The position of a swimmer from the beginning of a stroke cycle to the beginning of the next can be easily identified in a
video recording. However, this procedure has not been explored yet in the current literature with a sensor-based approach. Finally, velocity is another important variable that has not been fully explored using sensor-based methods. Based on the accurate identification of turn events, Siirtola (2011) has shown that it is possible to calculate the average velocity for each length. However, information about intracyclic velocity (i.e., the change in speed within the stroke cycle), which can be determined using video-based methods, still remains beyond the scope of sensor-based approaches. Intracyclic velocity is an important variable as it provides an opportunity to explore changes in velocity during different sections of a race or training distance (e.g., the first 100 m vs. the last 100 m of a 200 m swim).

### 2.3.3 Body roll analysis in swimming

The analysis of body roll in competitive freestyle swimming has been carried out in essentially two different ways. First, in several studies the roll of the trunk was calculated based on the assumption that the entire trunk rolls as a rigid segment while swimming (Beekman, 1988; Castro et al., 2007; Liu et al., 1993; Payton et al., 1999). Second, the shoulder and hip roll of swimmers has been measured separately (Psycharakis & Sanders, 2008; Sanders & Psycharakis, 2009; Yanai et al., 2000). Researchers have also estimated body roll using different methods: simulation methods (Liu et al., 1993), two-dimensional (Beekman, 1988; Castro et al., 2007; Payton et al., 1999) and three-dimensional video-based methods (Psycharakis & Sanders, 2008; Sanders & Psycharakis, 2009; Yanai, T. & Hay, 2000), accelerometer based approaches (Bächlin & Tröster, 2012; Barber & Barden, 2014) and IMU based...
techniques (Magalhaes, 2014). The findings of these studies are presented in this section.

Liu et al. (1993) developed the first computer simulation model to examine the effect of trunk roll on handpath during the pull phase in freestyle swimming. The trunk and right arm were modeled as two rigid segments, joined at the shoulder by a simple hinge joint. The rigid arm segment was assigned a pre-selected elbow flexion angle and the hand was made to move in a plane through the shoulder parallel to the sagittal plane of the rotating trunk. Payton, Hay and Mullineaux (1997) also carried out a simulation study, enabling the flexion and extension of the elbow. The results of these computer simulation studies were preliminary and could not be generalized until the models were established and validated. Nevertheless, the outcome of early computer simulation studies was useful in stimulating researchers’ interest in body roll and providing recommendations for further research.

Regarding the experimental studies that measured body roll as a rigid segment (Beekman, 1988; Castro et al., 2007; Payton et al., 1999), they all used a somewhat crude and rudimentary method. A balsa wood fin mounted on a curved aluminum base was strapped to the back of each swimmer (see Figure 11). A single camera was placed on the pool deck and swimmers were requested to swim away from the camera. Using these recordings, trunk roll was defined and calculated as the angle between the rear edge of the fin and the vertical axis. However, there are a considerable number of limitations associated with using this method. The assumption that the trunk moves as a rigid segment during freestyle swimming
does not allow for separate analysis of shoulder and hip roll and some studies have indicated that timing and magnitude of these two variables are different (Psycharakis & Sanders, 2008; Sanders & Psycharakis, 2009). In addition, the device attached to the swimmer is highly likely to interfere with the stroke technique, thereby modifying the parameters of body roll and stroke kinematics. Moreover, it could also move relative to the swimmer’s body as they move through the water making the recorded angles inaccurate.

Video-based studies that have calculated shoulder and hip roll separately have used 3D methods. For example, Psycharakis et al. (2008) used a system of four below- and two above water synchronized cameras, obtaining a 6.5-m long calibration space. The roll angles of the shoulders and hips in studies using this method were determined by projecting the vector of the respective right joint relative to the left joint onto the vertical plane perpendicular to the swimming direction (Psycharakis & Sanders, 2008; Sanders & Psycharakis, 2009), or by expressing the shoulder and hip roll angles relative to the long axis of the swimmer’s body (Yanai et al., 2000; Yanai, 2001).

More recently, accelerometers have been used as a tool for body roll analysis. Bächlin et al. (2012) analyzed twelve swimmers who consciously varied kick intensity and body roll during five pool lengths. The accelerometers were placed on the swimmers’ backs with the alignment shown in Figure 12. The x-axis was aligned with the longitudinal axis of the body (in line with the spine), the y-axis was perpendicular to the x-axis (mediolateral axis), and the z-axis was vertical with respect to the swimmer (and orthogonal to the x and y-axes). For a static case, the roll
angle can be determined from the measured gravity in the body coordinate system using Equation 2.3.

\[ \varphi_r = \arctan \left( \frac{y_b}{z_b} \right) \]  

(2.3)

However, swimming is not a static activity so a simulation was conducted in order to determine whether the irregular forward movement of the swimmer and the pitch angle had any effect on body roll. They compared the sensor signal with the calculation of the correct angle and showed that there was no difference. They concluded that the previous equation would also be valid for the non-static case of swimming. Using the same method, Barber & Barden (2014) compared the amount of body roll in freestyle swimmers during different breathing conditions. Their research also demonstrated that accelerometers provide body roll values that are consistent with those obtained by video-based methods.

Finally, Magalhaes (2014) measured joint kinematics of the upper limb with IMUs. They did not specifically measure body roll, but it can be assumed that the data collected by the IMUs would provide sufficient information to obtain the angular position of the trunk as well, as they used one of the IMUs horizontally in line with the shoulders. Mischie (2012) explained how to obtain angular positions based on the raw data given by the IMUs, specifically using angular velocity. IMUs provide an output voltage \( V_{out} (t) \), which depends on the angular velocity normal to one of the sensor’s three planes. This is represented in Equation 2.4.

\[ V_{out} (t) = S \omega(t) \]  

(2.4)
**Figure 12.** Alignment of the accelerometer’s axis. *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.*
\( \omega (t) \) represents the angular velocity in rad/s and \( S \) represents the gyroscope sensitivity in V/(rad/s). By integrating the angular velocity, the angular position \( \alpha (t) \) can be obtained as shown in Equation 2.5.

\[
\alpha(t) = \int \omega(t) \, dt
\]  \hspace{1cm} (2.5)

However, when body roll is measured there will not be a constant angular velocity, meaning there will not be an analytical expression of \( \omega (t) \), but successive values are available, which are obtained by the measurement process. If there are \( n \) measurement data, \( \omega_1, \ldots, \omega_n \), the angular position is updated once to \( n \Delta t \) seconds by Equation 2.6.

\[
\alpha (\tau + n\Delta t) = \alpha (\tau) + Area
\]  \hspace{1cm} (2.6)

In this case, \( Area \) is computed by the trapezoidal method. This way, we would be able to measure the angular position of the IMU at any specific point in time and, therefore, body roll angle.

2.4 Summary

A broad spectrum of information regarding swimming biomechanics, sensor usage for biomechanical analysis and shoulder pain presentation in swimmers has been reviewed. Based on this literature review, this study aimed to analyze body roll differences in swimmers with and without shoulder pain, using accelerometers as the measurement tool for this purpose.
3. METHODS

3.1 Participants

The experiment was carried out after being approved by the Research Ethics Board of the University of Regina. Participants were recruited from several swim clubs in Northern Spain in which the student had a relationship with the coach. A formal request was sent to the coach asking to notify the swimmers of the study. Interested swimmers identified by their coaches as adults with a provincial qualifying standard contacted the investigators and they were contacted by the principal investigator to verify their eligibility. Eligible participants were provided with an information sheet about the study and they signed an informed consent form prior to the experiment.

Two groups were used for the study. One was comprised of swimmers with unilateral shoulder pain, and the other was a control group of swimmers with healthy shoulders. The number of participants was based on an a priori power analysis conducted using values from previous studies that analyzed body roll (Barber & Barden, 2014; Beekman, 1988; Cappaert et al., 1995; Castro et al., 2007; Liu et al., 1993; Payton et al., 1999; Psycharakis & Sanders, 2008; Psycharakis & McCabe, 2011; Sanders & Psycharakis, 2009; Yanai, 2001). Given a power of 80%, an assumption of 5 degrees difference in body roll between groups and a standard deviation of 4 degrees, a total number of 24 participants (i.e., 12 for each group) were needed to detect a significant difference if one existed.

All participants answered a questionnaire prior to participating in the study to ensure they met the inclusion/exclusion criteria. In case any of the requirements were
not met, the swimmer was excluded from the study. The inclusion criteria for the participants was the following:

— They needed to be adults over 18 years of age.

— They needed to be competitive swimmers who train a minimum of 15,000 meters per week at the time of the study. This condition was applied to the two years prior to the study as well.

— They needed to have achieved (at minimum) a provincial championship qualifying standard in the current season. This ensured that all swimmers met the requirements to be considered elite competitive swimmers and that they had developed a consistent technique and, therefore, a consistent body roll.

— All participants needed to have a preferred breathing side, as they were asked to breathe to this side so that the breathing pattern between swimmers was consistent.

These inclusion criteria applied to all participants. However, the following additional criteria was only applied to participants in the shoulder pain group: 1) they needed to have experienced the same unilateral shoulder pain in the last 3 months at least twice per month and 2) their affected side needed to be opposite to their preferred breathing side (e.g., breathing to the left with right shoulder pain). The first condition ensured that the injury was chronic and that the pain was not an acute response to a sporadic cause (e.g., dryland workouts, overuse of paddles in a specific period, etc.) The second condition was based on the hypothesis regarding the mechanism that describes the relationship between body roll and shoulder pain.
In reference to the classification described by Neer & Welsh (1977) for swimmer’s shoulder, there are four phases in regards to pain severity: Phase I, pain only after heavy workouts; Phase II, pain (not disabling) during and after workouts; Phase III, disabling pain during and after workouts that interferes with the swimmer’s performance; and Phase IV, shoulder pain that prevents competitive swimming. In the last phase, pain at rest and sleep disturbances are common. Only participants in Phases I and II were included in this study. Phases III and IV were excluded as they involve disabling pain. This criterion helped to control the direction of causality. It is difficult to determine the direction of causality between mechanics and injury, in terms of whether altered mechanics cause the injury or the injury causes the altered mechanics. Therefore, trying to control these variables is crucial to avoid confounding results. The chances that a participant’s technique was modified in response to pain was reduced if swimmers who suffered disabling pain that interferes with their ability to practice were excluded. Additionally, the following exclusion criteria were also applied:

— Having undergone shoulder surgery, as structural changes of the anatomy could lead to biomechanical changes in the stroke.

— Having been assessed by a health professional in biomechanics of their stroke to improve their shoulder pain.

3.2 Data collection device

Two tri-axial accelerometers (GENEActiv, Cambridge, UK) were attached to each swimmer in this study. This accelerometer model is waterproof, small (36 mm x 30 mm x 12 mm) and lightweight (16 grams). Several studies have shown that
accelerometers provide body roll values that are consistent with those obtained by video-based methods (Bächlin & Tröster, 2012; Barber & Barden, 2014), and they were selected for use in this study because they can continuously measure body roll angle. One accelerometer was attached to the dorsal surface of the swimmer’s pelvis in line with the posterior inferior iliac spines. It was located in the middle of an imaginary line formed by these two structures. The second accelerometer was attached to the swimmer’s thoracic vertebrae at the level of the scapular spines. Elastic therapeutic tape (KT) was used to attach the accelerometers to the swimmer’s body.

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 (mediolateral axis of the body), and the z-axis vertical to the x and y-axes (Fig. 13). The accelerometer was set to sample at 100 Hz.

![Figure 13. Alignment of the accelerometer’s axis for the study. 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.](image-url)
3.3 Experimental protocol

The experiment was conducted in a 25m indoor pool. Swimmers first performed a fifteen-minute warm-up of their choice. Then they were asked to swim three repetitions (trials) of 100m freestyle. Each trial was completed at a different pace (as a reference, the provincial standard for this event in Saskatchewan is 59.67 seconds for male and 1:05.98 for female). One trial was at 140% of their current seasonal personal best time (slow), one at 130% (medium) and one at 115% (fast). This range of speeds attempted to simulate the speeds that are most commonly used during practice. It is important to measure body roll angle at different speeds as evidence suggests that speed has an inverse effect on body roll; i.e., as velocity increases, body roll decreases (Castro et al., 2007; Psycharakis & Sanders, 2008; Yanai, 2003). The order in terms of speed was randomly assigned by a computer which gave random combinations of the three speeds. Participants had a full recovery of 5 minutes between trials. This ensured that fatigue was not a variable that affected the participants differently. If participants failed to achieve the desired time by a difference superior to a 4% of the time, they were given full recovery to repeat it.

Before each trial, swimmers were required to lie face down on the pool deck for 10 seconds prior to entering the pool. This was done because different body shapes or slightly different placements of the device may have led to different sensor orientations. The data from this period of time was averaged to determine any offset (i.e., gravitational signal bias) due to sensor misalignment. Subsequently, the calculated shoulder and hip roll angles were adjusted to correct for the offset caused by sensor misplacement. Swimmers also performed a vertical jump in the water
before each trial to provide researchers with a pre-trial reference point which would appear in the data as a large acceleration peak in the y-axis. Subsequently, swimmers began their trial by pushing off the wall. At the end of the trial they repeated the vertical jump to indicate the termination point. To ensure breathing had the same effect on body roll angle, each participant was asked to breathe once per stroke cycle (i.e., every two strokes) to their preferred breathing side only. This condition was required so that every swimmer had a breathing side and a non-breathing side. This was the only way to compare body roll values between the pain group and control group with the same breathing conditions. This was important as swimmers roll their shoulders and hips to the breathing side significantly more than to the non-breathing side (Psycharakis & McCabe, 2011), probably to facilitate the turning of the head to take a breath (Payton et al., 1999; Yanai, 2001).

The accelerometers collected data during the entire 100m trial (four lengths). Previous studies that measured body roll angles using video-based methods (Beekman, 1988; Castro et al., 2007; Payton et al., 1999; Psycharakis & Sanders, 2008; Sanders & Psycharakis, 2009; Yanai, 2001) were only able to measure 1 or 2 stroke cycles per length. As mentioned previously, the accelerometer method allowed body roll angle to be measured continuously for each individual stroke, obtaining a better average that described more accurately the roll kinematics of freestyle swimmers with and without unilateral shoulder pain.

3.4 Data processing

GeneActiv Software designed specifically for the GeneActiv accelerometers was used to extract the raw data. Accelerations in the X, Y and Z-axis for each trial
were imported into Microsoft Excel for data processing. The raw X, Y and Z accelerations were processed using a digital filter. Based on previous studies that used the same accelerometers for the purpose of body roll angle measurement (Barber & Barden, 2014), a zero-lag Butterworth low pass digital filter was used with a cut-off frequency of 4 Hz. Hip and shoulder roll angles for each trial were calculated using the filtered acceleration data and the tangential Equation 3.1.

\[
\text{Body roll angle} = \arctan \left( \frac{X}{Z} \right) \tag{3.1}
\]

As was indicated in the experimental protocol, swimmers only breathed to their preferred side. Therefore, each swimmer had a peak shoulder/hip roll angle on the breathing side and a peak shoulder/hip roll angle on the non-breathing side. First, these values were averaged to obtain a mean peak body roll angle for each length. The average of the entire 100m trial (4 lengths) was used for the comparison between subjects.

Three different speed conditions were used as mentioned in the experimental protocol. Therefore, a total of 12 mean body roll angle values were obtained for each swimmer, as shown in Table 2. The degree of bilateral asymmetry between the breathing and non-breathing sides was also calculated using an asymmetry index (ASI) adapted from the one described by Carpes, Mota and Faria (2010). Equation 3.2 shows an example of the calculation for shoulder roll.

\[
\text{ASI}\% = \left( \frac{|SB - SNB|}{\frac{1}{2}(SB+SNB)} \right) \times 100 \tag{3.2}
\]
3.5 Statistical analysis

The independent variables in this study include group (pain vs. control group), speed (fast, medium and slow) and roll side (breathing vs. non-breathing). The dependent variables include peak body roll angle of both regions (shoulder and hip) and ASI. First, a repeated measures analysis of variance (RM ANOVA) was carried out to examine whether a significant main effect existed between the four lengths of the 100m trials. Given that swimmers were to maintain a constant pace throughout the trial, it was not expected that there would be any differences and this assumption was found to be correct. Regarding the analysis of body roll angle, each pairing of body roll region and side (SB, SNB, HB and HNB) was analyzed separately to determine the main effects of group and speed. Therefore, four factorial mixed ANOVAs were conducted in which the between-subjects independent variable was the group and the repeated measures independent variable was speed. Table 3 shows which variables were compared between groups in each of the analyses.

In regards to the ASI, another factorial ANOVA was conducted for each region (shoulder and hip) with the same independent variables as the previous analyses. We used IBM SPSS Statistics 22 to perform the analyses.
Table 2. Body roll angle values measured in each participant.

<table>
<thead>
<tr>
<th>Region</th>
<th>Breathing side (B)</th>
<th>Non-breathing side (NB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder roll (S)</td>
<td>SSB, MSB, FSB</td>
<td>SSNB, MSNB, FSNB</td>
</tr>
<tr>
<td>Hip roll (H)</td>
<td>SHB, MHB, FHB</td>
<td>SHNB, MHNB, FHNB</td>
</tr>
</tbody>
</table>

The first letter refers to speed (F/M/S), the second one to roll region (S/H) and the third one to roll side (B/NB).

Table 3. Variables for each of the factorial mixed ANOVAs.

<table>
<thead>
<tr>
<th>STATISTICAL ANALYSIS</th>
<th>REGION</th>
<th>SIDE</th>
<th>SPEED</th>
<th>GROUP</th>
<th>PAIN</th>
<th>CONTROL</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANOVA 1</td>
<td>Shoulder</td>
<td>Breathing side</td>
<td>Medium</td>
<td>MSB</td>
<td>SSB</td>
<td>SSB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fast</td>
<td>FSB</td>
<td>SSB</td>
<td>SSB</td>
</tr>
<tr>
<td>ANOVA 2</td>
<td>Non-breathing side</td>
<td>Medium</td>
<td>MSNB</td>
<td>MSNB</td>
<td>SSNB</td>
<td>SSNB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fast</td>
<td>FSNB</td>
<td>FSNB</td>
<td>FSNB</td>
</tr>
<tr>
<td>ANOVA 3</td>
<td>Breathing side</td>
<td>Medium</td>
<td>MHB</td>
<td>MHB</td>
<td>SHB</td>
<td>SHB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fast</td>
<td>FHB</td>
<td>FHB</td>
<td>FHB</td>
</tr>
<tr>
<td>ANOVA 4</td>
<td>Non-breathing side</td>
<td>Medium</td>
<td>MHNB</td>
<td>MHNB</td>
<td>SHNB</td>
<td>SHNB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fast</td>
<td>FHN B</td>
<td>FHN B</td>
<td>FHN B</td>
</tr>
</tbody>
</table>
Results were considered significant when $p$ values were less than 0.05. Main effects and interactions were broken down using planned contrasts (Bonferroni adjusted post-hoc tests) to analyze potential significances between different levels of speed. Based on the information given by the statistical results we used $F$-ratios ($F$) and degrees of freedom ($df$) to obtain the effect size ($r$) of the results using Equation 3.3 as described by Field (2013).

$$r = \sqrt{\frac{F}{F + df}} \quad (3.3)$$
4. RESULTS

Demographic characteristics of the subjects are reported in Table 4 along with the 100m freestyle event personal best average for males and females of each group and the years spent at competitive level. Within the pain group, number of subjects for Phases I and II of the swimmer’s shoulder –described by Neer & Welsh (1977)- are also reported.

Table 4. Subjects characteristics

<table>
<thead>
<tr>
<th></th>
<th>CONTROL GROUP</th>
<th>PAIN GROUP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y ± SD)</td>
<td>20.1 ± 3.5</td>
<td>22.9 ± 5.7</td>
</tr>
<tr>
<td>Sex</td>
<td>M: 6, F:6</td>
<td>M: 6, F:6</td>
</tr>
<tr>
<td>Height (cm ± SD)</td>
<td>177.6 ± 6.7</td>
<td>176.8 ± 8</td>
</tr>
<tr>
<td>Weight (kg ± SD)</td>
<td>70 ± 7.2</td>
<td>71.3 ± 7.8</td>
</tr>
<tr>
<td>100m Freestyle PB (s)</td>
<td>M: 54.6, F: 60.6</td>
<td>M: 54.0, F: 62.8</td>
</tr>
<tr>
<td>Competitive level (y ± SD)</td>
<td>11.3 ± 3.5</td>
<td>13.1 ± 4.4</td>
</tr>
<tr>
<td>Swimmer’s shoulder phase</td>
<td>-</td>
<td>I: 3, II: 9</td>
</tr>
</tbody>
</table>

y=years, SD=Standard Deviation, M=Male, F=Female, PB= Personal Best, s=seconds

Mean peak body roll angles and standard deviations are reported in Table 5. Significance of the difference between groups is presented as the “p” value and the effect size as the “r” value for each variable. No statistically significant differences were found in roll at the shoulder region between swimmers with and without shoulder pain. However, healthy swimmers showed an overall tendency to have greater roll in all variables, regardless of speed and rotation side.
Table 5. Peak body roll angles and significant differences. Angles represented as mean ± standard deviation.

<table>
<thead>
<tr>
<th>REGION</th>
<th>SIDE</th>
<th>SPEED</th>
<th>GROUP</th>
<th>DIFFERENCE</th>
<th>“p” Value</th>
<th>Effect size (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>PAIN</td>
<td>CONTROL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder</td>
<td>Breathing</td>
<td>Slow</td>
<td>81.78 ±14.82</td>
<td>84.39 ±11.04</td>
<td>0.593</td>
<td>0.477</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium</td>
<td>76.29 ±12.32</td>
<td>79.67 ±8.34</td>
<td>0.593</td>
<td>0.477</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fast</td>
<td>75.53 ±13.13</td>
<td>76.93 ±7.92</td>
<td>0.593</td>
<td>0.477</td>
</tr>
<tr>
<td></td>
<td>Breathing</td>
<td>Slow</td>
<td>67.57 ±11.81</td>
<td>71.53 ±12.21</td>
<td>0.621</td>
<td>0.619</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium</td>
<td>66.44 ±11.43</td>
<td>67.98 ±7.62</td>
<td>0.621</td>
<td>0.619</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fast</td>
<td>65.32 ±10.52</td>
<td>65.89 ±7.04</td>
<td>0.621</td>
<td>0.619</td>
</tr>
<tr>
<td></td>
<td>Non-breathing</td>
<td>Slow</td>
<td>65.08 ±8.44</td>
<td>66.48 ±6.23</td>
<td>0.500</td>
<td>0.566</td>
</tr>
<tr>
<td></td>
<td>Breathing</td>
<td>Slow</td>
<td>62.80 ±7.89</td>
<td>65.15 ±7.34</td>
<td>0.500</td>
<td>0.566</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fast</td>
<td>61.01 ±7.98</td>
<td>63.51 ±8.19</td>
<td>0.500</td>
<td>0.566</td>
</tr>
<tr>
<td></td>
<td>Breathing</td>
<td>Slow</td>
<td>*50.19 ±9.37</td>
<td>58.25 ±7.44</td>
<td>0.018</td>
<td>0.931</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium</td>
<td>*48.46 ±9.24</td>
<td>56.61 ±7.04</td>
<td>0.018</td>
<td>0.931</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fast</td>
<td>*47.93 ±8.53</td>
<td>55.38 ±7.68</td>
<td>0.018</td>
<td>0.931</td>
</tr>
</tbody>
</table>

*Significantly different from Control Group

In regards to the hip region, a statistically significant group main effect for the non-breathing side was found, in which the hip rolled (as an average of the three speeds) 48.8 degrees for the pain group (95% CI: 43.91, 53.8) versus 56.7 degrees for the healthy group (95% CI: 51.8, 61.7). Therefore, swimmers with shoulder pain rolled significantly less to the non-breathing side (p=0.018, r=0.931). This difference between groups was found to be significant for the three speeds in the post-hoc tests:
slow (p=0.029), medium (p=0.024) and fast (p=0.035). Conversely, no significant differences between groups were found on the breathing side at the hip region.

There was also a significant main effect for speed (p<0.02), due to a reduction in roll angle at the shoulder and hip regions for both groups when speed increased. All post-hoc comparisons supported this effect, with the exception of hip roll angle on the non-breathing side. There was a reduction of roll angle for this variable as well, but the difference between speed levels was not statistically significant (p=0.091). There were no significant interaction effects between speed and group for any of the conditions, meaning that changes in roll angle due to speed were the same for both groups.

All the aforementioned body roll variables including the variation among speed levels are shown in Figure 14.
Figure 14. Mean peak body roll angles for both groups at the hips and shoulders for the 3 different speeds. Vertical bars represent 95% confidence intervals.
The second set of statistical analyses was conducted in order to determine whether a difference in bilateral asymmetry between groups existed. The results are reported in Table 6 as percentages of side-to-side asymmetry and standard deviations at the two regions and three speed levels. Both groups showed a positive bilateral asymmetry, which indicates a greater roll to the breathing side. The ASI at the shoulder level was similar in both groups, 16% in the control group versus 16.1% in the pain group, not representing a significant difference (p=0.986). In contrast, there was a statistically significant difference between groups at the hips ASI (p=0.018). Subjects in the control group showed an average ASI of 13.79% (95% CI: 6.8, 20.7) whereas pain group ASI was 25.96% (95% CI: 19, 32.9).

Table 6. Side to side breathing asymmetry index (%). Represented as mean ±SD.

<table>
<thead>
<tr>
<th>REGION</th>
<th>SPEED</th>
<th>GROUP</th>
<th>DIFFERENCE</th>
<th>“p” Value</th>
<th>Effect size (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder</td>
<td>Slow</td>
<td>PAIN</td>
<td>19.0 ±12.8</td>
<td>16.8 ±16.6</td>
<td>0.986</td>
</tr>
<tr>
<td>Shoulder</td>
<td>Medium</td>
<td>PAIN</td>
<td>14.1 ±11.7</td>
<td>15.8 ±12.5</td>
<td>0.986</td>
</tr>
<tr>
<td>Shoulder</td>
<td>Fast</td>
<td>PAIN</td>
<td>15.2 ±9.6</td>
<td>15.4 ±13.4</td>
<td>0.986</td>
</tr>
<tr>
<td>Shoulder</td>
<td>Slow</td>
<td>CONTROL</td>
<td>13.5 ±10.6</td>
<td>13.5 ±10.6</td>
<td>0.986</td>
</tr>
<tr>
<td>Hip</td>
<td>Medium</td>
<td>PAIN</td>
<td>*26.6 ±16.5</td>
<td>14.1 ±9.9</td>
<td>0.018</td>
</tr>
<tr>
<td>Hip</td>
<td>Fast</td>
<td>PAIN</td>
<td>*24.6 ±16.9</td>
<td>13.7 ±10.5</td>
<td>0.018</td>
</tr>
</tbody>
</table>

*Significantly different from Control Group
5. DISCUSSION

The purpose of this study was to analyze the potential relationship between body roll angle and shoulder pain in elite competitive freestyle swimmers. Specifically, this study looked at a particular presentation of the condition known as swimmer's shoulder, in which a swimmer experiences pain in the opposite shoulder to their preferred breathing side. It was hypothesized that swimmers with this pain presentation would roll less to the non-breathing side compared to healthy swimmers if they all maintained a consistent breathing pattern to avoid variations due to this variable. The second hypothesis was that they would also have a larger bilateral asymmetry due to the previous hypothesis and to a potential increased roll to the breathing side. These hypotheses were formulated based on two mechanisms described in the literature as potentially harmful for the shoulder region. The first one states that an insufficient body roll to one side causes an augmented horizontal abduction of the ipsilateral arm during the recovery phase, potentially increasing the stress suffered by the long head of the biceps and supraspinatus tendons against the coracoacromial arch (Richardson et al., 1980). Bak and Fauno (1997) also hypothesized that breathing to one side may increase the risk of injury on the contralateral shoulder. They explained that breathing to one side is often associated with an insufficient body roll to the opposite side, requiring additional horizontal abduction of the shoulder complex and, therefore, an increase in stress on the anterior side of the joint during the recovery phase. Similarly, Davies et al. (2008) suggested that swimmers who consistently turn their heads to the same side to breathe are risking shoulder pain in the opposite shoulder. They argued that this causes the
swimmer to work harder with the contralateral pulling arm to support forward movement with the head turned to the side, which leads to overuse conditions.

The data reported in this study shows a partial reduction in body roll to the affected side in swimmers with unilateral shoulder pain, which supports this hypothesis based on the described mechanism. However, the difference in body roll only occurred at the hips, and body roll at the shoulder region was similar between swimmers with and without shoulder pain. Significant differences at the shoulder level would further support this injury mechanism, but the fact that only hip roll was significantly different highlights the need to revise this theory to further explain why this relationship between body roll and shoulder pain may exist. Nevertheless, the hip region itself has been shown to heavily influence shoulder range of movement in other sports (Oyama et al., 2014) as well as modifying muscle activation patterns at the shoulder girdle (Yamauchi et al., 2015). In addition, the pelvic girdle has been described in the literature as an important contributor to generate movement through the kinetic chain of the shoulder (Chu, Jayabalan, Kibler, & Press, 2016; Sciascia, Thigpen, Namdari, & Baldwin, 2012; Wilk, Arrigo, Hooks, & Andrews, 2016). Another possible explanation to explain the discrepancy between the shoulder and hip region results could be the one proposed by Laudner & Williams (2013), in which scapular movement abnormalities were found in swimmers with latissimus dorsi stiffness. Pulling with the hand that has more trunk rotation (due to a decreased hip rotation) would increase the tension of this muscle, potentially increasing the load at the shoulder joint. However, this study was performed with asymptomatic swimmers, so no clear relationship was established between latissimus dorsi stiffness and shoulder pain. Based on the results of the present study, it is suggested that a
decreased hip roll to the non-breathing side not only increases the horizontal abduction of the shoulder, but may also cause the shoulder to work harder when propelling the hand forwards during the arm recovery to initiate body roll to the opposite side. In other words, a greater body roll to the non-breathing side could reduce the energy required by the shoulder joint to advance the hand during the arm recovery and to initiate the rotation of the body to the breathing side, as the kinetic chain would be in a more advantageous position to place a higher demand on the trunk for force production.

The second hypothesis stated that swimmers with shoulder pain would have a greater bilateral asymmetry in body roll than healthy swimmers, due to a reduced roll to the non-breathing side and an increased roll to the breathing side. This was based on the mechanism that a greater body roll to the preferred breathing side causes the arm of the opposite side to pull through a longer distance. This could potentially increase the muscle workload and fatigue on this side and could lead to a weakening of the capsuloligamentous complex, during a phase in which a greater demand is placed on the shoulder in the maximum abduction/flexion and external rotation position (Turkel et al., 1981).

The data from this study partially supports our hypothesis, in that a significantly greater hip roll asymmetry was found in swimmers with shoulder pain, which was not evident at the shoulder level. This difference with respect to the level of asymmetry is consistent with our previous result, in which a significant difference between groups was found at the hip for the non-breathing side. Beekman (1988) reported significant differences between breathing and non-breathing conditions for a
group with shoulder injury (breathing body roll: 60°; non-breathing body roll: 48°), but no differences for an injury-free group (breathing body roll: 54°; non-breathing body roll: 55°). However, no specific presentation of shoulder pain was analyzed in this study. In contrast to these results, this data shows that bilateral asymmetry was present in both groups, caused by a greater roll to the breathing side. This is consistent with data from other authors such as Payton et al. (1999), who found that swimmers rolled on average 9° more during the breathing (66°) than the non-breathing trial (57°). Castro et al. (2007) also reported that most of their swimmers rolled more when breathing. However, in this study bilateral asymmetry of the hips was greater in swimmers with shoulder pain, because they rolled less to the non-breathing side.

In order to obtain consistent body roll values in this study, two variables that have been described as potential contributors to body roll modification were controlled: swimming speed and breathing pattern. Interestingly, body roll values reported in this study are consistent with previous studies in which breathing and non-breathing roll values were specified (Barber & Barden, 2014; Castro et al., 2007; Liu et al., 1993; Payton et al., 1999) and differ from those in which values were reported regardless of breathing conditions (Cappaert et al., 1995; Yanai, 2001). Body roll values in this study also differ from those reported by Psycharakis and Sanders (2008; 2009) for non-breathing conditions. An explanation for the discrepancy with these studies is that they required subjects to control their breathing patterns through a 6.75 m³ 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
In regards to the effect of speed on body roll, these results are consistent with those reported by Castro et al. (2007) and Psycharakis and Sanders (2008), in which it was reported that body roll in swimmers decreased when speed increased. We found that body roll decreased in both groups and in both locations when speed was increased and the difference between speed levels was statistically significant for all variables except for hip roll on the non-breathing side. Consequently, the evidence is consistent with the findings of previous studies and suggests that increasing speed leads to an overall reduction in body roll.

5.1 Limitations of the study

This study is not without limitations. The gold standard method in swimming biomechanics analysis is 3D video recording and, to my knowledge, no comparison of the accelerometer based approach vs. the camera-based approach has been conducted. While it is conceivable that there could be some differences between the two methods, it is not clear which method is the most accurate (as camera-based methods also have potential sources of error as was discussed previously). Further, the values obtained for body roll in this study are consistent with those reported in other studies, and it is also the case that any potential errors should be systematic (i.e., constant) errors that would not affect the outcome of the statistical comparisons. Given that previous studies have used accelerometers for the same purpose (and
obtained results consistent with those from video recording), it was decided to use this tool as our data collection device.

A second potential limitation is related to the direction of causality. It is assumed that swimmers with shoulder pain did not change their technique after the onset of pain, or more exactly, that the biomechanics are the cause and pain is the consequence. Nevertheless, this might not be the case for every swimmer as some of them may have changed their technique unconsciously to avoid pain. As mentioned previously (see section 3.1), measures were taken to control this variable by excluding swimmers who suffered disabling pain that interfered with their ability to practice or experienced pain during the experiment. The chances that a participant modified their technique in response to pain was minimized in this way.

5.2 Significance of the study

The results of this study add knowledge to a limited, but growing body of research that has investigated the relationship between body roll and shoulder pain in competitive freestyle swimmers. There are numerous studies that have investigated the importance of the kinetic chain in sports like baseball (Chu et al., 2016), but they are not as common in swimming research. Previous studies that analyzed body roll in swimmers with shoulder pain were not specifically looking at this relationship and failed to identify a pattern between these two variables (Beekman, 1988). Nevertheless, many authors have recommended body roll enhancement as a tool to prevent or improve shoulder pain as it can help to minimize extreme positions of the shoulder that may occur during the stroke (Davies et al., 2008; Penny & Smith, 1980;
Richardson et al., 1980). However, the evidence in support of these statements is sparse and few experimental studies have been carried out in this area.

Based on previous research, this study developed a systematic approach to analyze body roll in order to control for the key factors that determine its outcome (i.e., swimming speed and breathing pattern). The methods of previous studies have been heterogeneous, and have not controlled for all the variables affecting body roll. This study is the first to report body roll values at both the hips and the shoulders, to allow the swimmers to breathe to their preferred side while keeping a consistent breathing pattern (i.e., between participants), has reported separate values for the breathing and non-breathing sides, and has conducted the analysis at three different swimming speeds. In addition, a specific swimmer’s shoulder subgroup with unilateral pain on the non-breathing side was generated so as to provide a coherent hypothesis based on potentially harmful mechanisms that have been described in the literature.

5.2 Future research

While these findings are promising, the results demonstrate the need for future research to further explore the relationship between body roll and shoulder pain. The use of the accelerometer approach is recommended to analyze body roll, as well as the proposed protocol to control for speed and breathing pattern, and it is encouraged that researchers analyze all the different presentations within the swimmer’s shoulder category. From a biomechanical perspective, five possible subgroups within the swimmer’s shoulder syndrome are proposed: 1) unilateral breathing pattern with pain on the non-breathing side, 2) unilateral breathing pattern with pain on the breathing
side, 3) unilateral breathing pattern with bilateral shoulder pain, 4) bilateral breathing pattern with unilateral shoulder pain, and 5) bilateral breathing pattern with bilateral shoulder pain. It is also recommended to preserve the body roll division between shoulder and hip regions to further analyze the discrepancy found in this study, as well as to add potential analyses of trunk rotation range of motion (ROM) in the laboratory. This would allow researchers to have a ROM reference value for each swimmer, and to analyze body roll as a percentage of their total range of movement.
6. CONCLUSION

This study demonstrated that swimmers with unilateral shoulder pain on the non-breathing side rolled their hips significantly less to the affected side than healthy swimmers, and that their bilateral asymmetry index was greater in terms of the amount of hip rotation. This supports the idea that a relationship may exist between body roll and shoulder pain in freestyle swimmers, but prospective studies should be carried out to better understand the reason and mechanisms responsible for this relationship. This study employed a systematic, accelerometer-based approach based on previous research and minimized confounding factors that have been shown to affect body roll.
List of References


acromiohumeral distance matter in chronic rotator cuff related shoulder pain?

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CONSENT FORM

BODY ROLL DIFFERENCES IN FREESTYLE SWIMMING
BETWEEN SWIMMERS WITH AND WITHOUT SHOULDER PAIN

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PURPOSE OF THE STUDY:

The purpose is to investigate whether differences in body roll exist between swimmers with and without shoulder pain. To quantify this parameter, body-fixed sensors (accelerometers) will collect motion data on elite swimmers, which will help to improve the current understanding regarding shoulder injury prevention and the causes of shoulder pain. It will provide the opportunity to monitor and assess the angle of body roll of two groups of swimmers (with and without shoulder pain) and to compare the obtained values between those two groups.

PROCEDURE:

Two accelerometers will be attached to your upper and lower back. The sensors are non-invasive and small (about the size of a watch) and will be placed at the level of your shoulder blades, and at the lower back (S2) using therapeutic elastic tape. You will perform a regular warm-up immediately prior to testing. Subsequently you will perform three trials of 100 meters freestyle. One will be carried out at a fast speed, one at a medium speed and one at a slow speed. The order of these will be randomly assigned. The session will take around 30 minutes.

RISKS/BENEFITS:

There are no known risks associated with participating in this study (other than those that might occur normally as a result of training). The sensors will be attached to your body in a way that will not interfere with your movement. You can stop swimming at any point during the data collection process. Your participation will help provide data to coaches and physical therapists that will be used to prevent, diagnose and treat shoulder problems in swimmers.

CONFIDENTIALITY/FREEDOM TO WITHDRAW:

Your data will be shared with your coach and staff of your team. You will be notified by your coach when your data is available and you will also be able to obtain it. If your data is shared outside of this group (e.g., conference presentation) it will be reported using an anonymous subject code and trial number (e.g., Subject 1a). Two months after your participation withdrawal of your data will no longer be possible. Your participation is strictly voluntary and you can withdraw from the study at any time.
To be completed by the participant:

Have you read and fully understood the information above? Yes No
Do you understand the benefits and risks involved in taking part in this study? Yes No
Have you had an opportunity to ask questions about the study and its procedures? 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

This study was explained to me by: ____________________________

I agree to take part in this study.

________________________________________________________________________
Signature of participant Date Witness
________________________________________________________________________
Printed Name 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 (306) 585-4775 or by e-mail at research.ethics@uregina.ca. Your participation (or lack thereof) or withdrawal from this study at any time will not affect your status on your team. Should you have any questions or wish to discuss the procedures or objectives of the study, please contact Oscar Vila Dieguez by phone at (306) 209-1037 or e-mail at vila2000e@uregina.ca.