Relationship Between Freestyle Biomechanical Errors and Shoulder Pain in Elite Competitive Swimmers

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ABSTRACT

BONNIE VIRAG: Relationship Between Freestyle Biomechanics and Shoulder Pain In Elite Competitive Swimmers
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Biomechanical freestyle stroke errors are thought to be risk factors for the development of shoulder pain among swimmers. The aim of this study was to examine the relationship between freestyle stroke biomechanical errors and shoulder pain in elite competitive swimmers. Thirty-one swimmers from an elite competitive population completed two Penn Shoulder Score questionnaires (one per shoulder) for evaluation of shoulder pain, satisfaction, and function. Each swimmer was instructed to swim freestyle for two lengths of a 25 yard competitive swimming pool which was filmed from both above water and underwater cameras, providing frontal and lateral views. The biomechanics were analyzed and clipped using Dartfish TeamPro™ software. Presence of errors was determined by selected evaluators and this data was used to determine if freestyle biomechanical errors predicted shoulder pain. Neither the total number of biomechanical freestyle errors, nor any of the specific errors were predictive of the PENN shoulder pain score.

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CHAPTER I

INTRODUCTION

AN OVERVIEW OF SWIMMER'S SHOULDER

Swimming the freestyle stroke places significant stress on the shoulder. In addition to a high amount of upper-extremity repetition due to training, the shoulder provides immense propulsive force during the freestyle stroke (Johnson, Gauvin, & Fredericson, 2003). Continual repetition and intense demand are consistently placed on the shoulder causing it to be the most commonly injured joint in swimming athletes (Stocker, Pink, & Jobe, 1995). Further, 42-87 percent of swimmers have reported shoulder pain at some time in their athletic careers (Beach, Whitney, & Dickoff-Hoffman, 1992; Richardson, Jobe, & Collins, 1980). "Swimmer's shoulder" is a general term frequently used to describe shoulder pain or injury experienced by a competitive swimmer (McMaster, Roberts, & Stoddard, 1998). A major cause of these shoulder problems experienced by front crawl swimmers is thought to be impingement of subacromial structures in the shoulder during their stroke (Yanai, Hay, & Miller, 2000). Significantly higher incidence rates for subacromial impingement have been found among swimmers compared to other overhead athletes performing at the NCAA Division I level (Laudner & Sipes, 2009).

COMMON TRAINING TRENDS IN COMPETITIVE SWIMMING

Current philosophy in competitive swimming indicates that swimmers build cardiovascular endurance and conditioning during an endurance phase and taper training near competitive events (Salo & Riewald, 2008). While 80 percent of competitive swimming events last two minutes or less, this philosophy indicates that a large volume of yardage in practice is necessary to be successful, even in these short events (Trappe, 1995). Analogous to this rationale, the swim season lasts 10-12 months and competitive swimmers practice 5-7 days per week, often twice daily (Beach, et al., 1992). On average, swimmers at the collegiate level train between 40,000 and 50,000 yards per week and an elite swimmer may log up to 20,000 yards in one day (McMaster & Troup, 1993; Stocker, et al., 1995). Successful performance in competitive swimming requires a unique mixture of endurance and power, which is developed through high loads of training. A well-developed cardiorespiratory system acquired through ample amounts of swimming is the foundation for power and strength development (Salo & Riewald, 2008). Not only does high frequency of in-water training enhance the muscular strength and cardiovascular endurance of these athletes, it is also thought to help develop and maintain a swimmer's feel of the water. This refers to a swimmer's intuitive ability to feel and effectively handle the water, a skill that is honed and preserved only through regular swimming practice (Colwin, 2002). In order to complete this amount of yardage during practice time, 80 percent of practice is completed in freestyle, regardless of stroke specialty. This allows the swimmers to complete the necessary yardage during practice time, but also places tremendous stress on the shoulder. It has been estimated that competitive swimmers will average about 18,000 shoulder revolutions per week mostly from the freestyle training (Beach, et al., 1992; M. Pink, Perry, Browne, Scovazzo, & Kerrigan, 1991). Because of the demand placed on the shoulder due to freestyle training, it is important to understand stroke biomechanics and their potential contribution to injury.

FREESTYLE STROKE BIOMECHANICS

Current research on proper swimming biomechanics is limited, making it difficult for any coach, swimmer, or investigator to agree on the correct freestyle stroke technique that both improves performance and decreases the risk of shoulder injury. A majority of the swimming literature seeks to identify stroke characteristics that can improve performance (Colwin, 2002; Salo & Riewald, 2008). Swimming kinematics such as stroke rate, length, velocity, swim efficiency, power and coordination of arm movements have been a focus of biomechanical research (Bielec & Makar, 2010; Toussaint et al., 1988). Coaching literature on swimming biomechanics has often been the product of swimming coaches and talented athletes acquiring knowledge through trial and error (Colwin, 2002). Unfortunately, the development of swimming mechanics has concentrated more on performance increases, and has less often focused on biomechanical advancements to contend with the vigorous demands place on the swimmer's shoulder.

Swimming research has sought to improve stroke performance through several studies in which freestyle biomechanics during front crawl have been examined (Johnson, et al., 2003; M. Pink, et al., 1991; Scovazzo, Browne, Pink, Jobe, & Kerrigan, 1991; Yanai & Hay, 2000; Yanai, et al., 2000). While most studies have focused on performance advancement, some studies have identified errors in freestyle biomechanics that may place the swimmer in vulnerable position for injury (Heinlein & Cosgarea, 2010; Johnson, et al., 2003; Richardson, et al., 1980; Yanai & Hay, 2000; Yanai, et al., 2000). The hand entry and initial catch phase of the stroke should occur forward and lateral to the head, medial to the shoulder (M. Pink, et al., 1991). Improper hand entry position occurs as hand enters away from midline and humerus is low to water due to dropped elbow (Scovazzo, Browne et al.

1991). The early pull-through phase of the freestyle stroke, begins when the hand enters the water and ends once the humerus is perpendicular to the axis of the torso (M. Pink, et al., 1991). The arm should move in a straight line rather than an S-shaped pulling pattern, avoiding incorrect excessive horizontal adduction (Johnson, et al., 2003). Completion of the late pull-through phase should finish when the palm approaches the thigh with the palm rotated inward. A dropped elbow during this part of the pull phase is a stroke error, increasing external rotation and horizontal adduction, and placing increased stress on the shoulder complex (Yanai and Hay 2000). In the recovery phase the hand should exit early from the water and the elbow should follow behind the wrist throughout the arc of motion (Scovazzo, et al., 1991; Yanai & Hay, 2000). A recovery exhibiting a shorter, lower arc of the arm and a dropped elbow indicates an error in this stroke phase. Although these errors have been identified as possible contributors to shoulder injury and pain in swimmers, there is no literature that clearly identifies the relationship between these biomechanical errors and shoulder pain in competitive swimmers. It has been demonstrated that male collegiate swimmers are subject to shoulder impingement about 25 percent of their freestyle stroke time with proper biomechanics (Yanai & Hay, 2000). This is important because the amount of time spent in an impingement position would hypothetically increase with improper freestyle technique. Therefore, flawed freestyle technique may increase the time spent in the impingement position during front crawl swimming, stress the anterior shoulder structures, and be a major contributor to shoulder pain and pathology (Johnson, et al., 2003; Wilk, Reinold, & Andrews, 2009; Yanai & Hay, 2000; Yanai, et al., 2000).

PURPOSE AND CLINICAL RELEVANCE

While swimming technique has been examined to make improvements in stroke efficiency and swimming speed, there is a lack of research on freestyle pathomechanics and their relationship to shoulder pain. Incorrect freestyle stroke biomechanics have been suggested as a possible risk factor for shoulder pain and pathology, but this has not been clearly observed in biomechanical or clinical studies (Johnson, et al., 2003; Yanai & Hay, 2000; Yanai, et al., 2000). While it has been suggested that faulty freestyle stroke mechanics may precede shoulder pain, there is still an unclear correlation between the two variables within swimming literature. Research is needed in the swimming world to help coaches and Athletic Trainers identify errors in freestyle stroke biomechanics and to prevent injury to the competitive swimming athlete. Therefore, the purpose of this study is to examine the relationship between freestyle stroke biomechanical errors and shoulder pain in elite competitive swimmers.

Research Questions

- *RQ 1*: Does the total number of biomechanical freestyle stroke errors predict shoulder pain score in elite competitive swimmers?
- *RQ 2*: Does the presence of specific biomechanical freestyle stroke errors predict shoulder pain score in elite competitive swimmers?
    - *RQ 2.1*: Does the presence of a thumb first hand entry position predict shoulder pain score?
    - *RQ 2.2*: Does the presence of an improper hand placement at hand entry (excessive lateral or excessive medial hand entry) predict shoulder pain score?

    - *RQ 2.3*: Does the presence of excessive horizontal adduction/S-shaped pull during the pull-through phase predict shoulder pain score?
    - *RQ 2.4*: Does the presence of a dropped elbow during the pull-through phase predict shoulder pain score?
    - *RQ 2.5*: Does the presence of a dropped elbow during the recovery phase predict shoulder pain score?
    - *RQ 2.6*: Does the presence of excessive or a lack of body roll during the recovery phase predict shoulder pain score?
    - *RQ 2.7*: Does the presence of an eyes forward head carriage position predict shoulder pain score?

RESEARCH DESIGN

- Cross sectional design

PREDICTOR VARIABLES

- Biomechanical Errors
    - Thumb first hand entry
    - Improper hand entry position of excessive horizontal adduction or lateral placement
    - S-shaped pull-through/excessive horizontal adduction
    - Dropped elbow during pull-through
    - Excessive or lack of body roll during recovery phase
    - Dropped elbow during recovery phase
    - Eyes forward head carrying position
- Total Error Score

    - Calculated as the total number of individual biomechanical errors

CRITERION VARIABLE

- The Penn Shoulder Score for pain and satisfaction of function

HYPOTHESES

- *H 1:* The total number of freestyle biomechanical errors will predict shoulder pain score in elite competitive swimmers.

- *H 2:* The presence of specific freestyle biomechanical errors will predict shoulder pain score in elite competitive swimmers.
    - *H 2.*1: The presence of a thumb-first hand entry will predict shoulder pain score in elite competitive swimmers.
    - *H 2.*2: The presence of a hand that crosses the long axis midline of the body or that is placed lateral to shoulder at entry will predict shoulder pain score in elite competitive swimmers.
    - *H 2.*3: The presence of an S-shaped pull-through or excessive horizontal adduction during pulling will predict shoulder pain score in elite competitive swimmers.
    - *H 2.*4: The presence of a dropped elbow during the pull-through phase will predict shoulder pain score in elite competitive swimmers.
    - *H 2.*5: The presence of a dropped elbow during the recovery phase will predict shoulder pain score in elite competitive swimmers.
    - *H 2.*6: The presence of body roll that is greater or less than the 35-45° will predict shoulder pain score in elite competitive swimmers.

- *H 2.7*: The presence of an eyes forward head carriage position will predict shoulder pain score in elite competitive swimmers.

NULL HYPOTHESES:

- The number of freestyle biomechanical error will not predict shoulder pain score in elite competitive swimmers.

- The presence of specific freestyle biomechanical errors will not predict shoulder pain score in elite competitive swimmers.

OPERATIONAL DEFINITIONS

- Elite competitive swimmer
    - Swimmer who trains at least 5 times per week, 1-2 hours each practice session, and has had at least 5 years of competitive swimming experience.
- Correct Freestyle stroke biomechanics: Swimming technique for the freestyle stroke based on the following parameters:
    - Fingers-first or little finger-first entry (Johnson, et al., 2003; M. Pink, et al., 1991)
    - Hand enters lateral to head and medial to shoulder (M. Pink, et al., 1991)
    - Straight back pull-through (Colwin, 2002; Johnson, et al., 2003)
    - Elbow kept higher than wrist, pointing laterally, reaching maximum bend at half-way through pull (Colwin, 2002)
    - Elbow kept higher than wrist throughout the recovery phase (Colwin, 2002; Wilk, et al., 2009)

  - Body roll near 45° along the longitudinal axis of the body (Johnson, et al., 2003)
  - Head in neutral position. Imagine line through center of head and extending length of the spine. (Johnson, et al., 2003)

- Freestyle stroke biomechanical errors: Presence of one of the following incorrect freestyle stroke biomechanics
  - Thumb-first hand entry (Johnson, et al., 2003)
  - Hand crosses the long axis midline of the body or is placed lateral to shoulder at entry (Johnson, et al., 2003; Scovazzo, et al., 1991)
  - S-shaped pull-through or excessive horizontal adduction during pulling (Johnson, et al., 2003; Wilk, et al., 2009; Yanai & Hay, 2000)
  - Dropped elbow during pull-through phase (Richardson, et al., 1980)
  - Dropped elbow during recovery phase (Richardson, et al., 1980; Wilk, et al., 2009)
  - Body roll that is greater or less than the 35-45° (Johnson, et al., 2003)
  - Head carriage is in eyes forward position. (Johnson, et al., 2003)

ASSUMPTIONS

- Swimmers will exhibit their normal freestyle mechanics while being filmed
- Swimmers will report their level of shoulder pain honestly
- The training regimens of this swimming program were comparable with other club swimming programs across the country during the time of the study

LIMITATIONS

- This is a correlational study and cannot demonstrate a cause and effect relationship between shoulder pain scores and biomechanical errors.
- Stroke biomechanics were captured only one time during the competition season and the swimmers' strokes may change throughout the season

DELIMITATIONS

- Swimmers were volunteers from a local club swimming team and must be collegiate or senior level swimmers (age 15-17)
- Swimmers were blinded to the specific objective of filming in relation to this study

CHAPTER II

REVIEW OF THE LITERATURE

SHOULDER PAIN AND COMPETITIVE SWIMMING

There is a prevalence of shoulder pain in competitive swimmers. A 73 percent injury incidence of interfering shoulder pain has been identified in elite competitive swimmers (McMaster & Troup, 1993). Overuse injuries occur in swimmers due to the excessive stress placed on the shoulder from common physical characteristics exhibited by swimmers, training program trends, and faulty swimming biomechanics.

Physical Characteristics of Swimmers

Swimmers often display a distinct set of physical characteristics, which can potentially predispose them to shoulder dysfunction and pain. A forward head, rounded shoulders, and kyphotic thoracic spine posture due to tight pectoralis major and minor muscles is one common to swimmers and can have negative effects on the shoulder girdle (M. M. Pink & Tibone, 2000). The pectoralis major muscle displays high amounts of activity during the pull-through phase of freestyle which, through high volumes of swimming, can become tight, leading to adverse muscle imbalances among the shoulder (M. Pink, et al., 1991). These athletes also have tendencies to display limited internal rotation range of motion of their shoulders, especially those swimmers with painful shoulders (Bak & Magnusson, 1997; Beach, et al., 1992). Additionally, hypermobility in shoulder external rotation range of motion is a common characteristic of competitive swimmers (Beach, et al., 1992). It is not unusual for swimmers to display increased humeral translation and laxity in their shoulders as well (M. M. Pink & Tibone, 2000; Tovin, 2006). These common physical characteristics found among the swimming population have the potential to create abnormal joint function, muscle imbalances, and increased stress on the shoulder, resulting in shoulder pain that causes substitutions among a typically normal freestyle stroke (M. M. Pink & Tibone, 2000).

Training Trends

Competitive swimming practice trends have been thought to contribute to shoulder injury (Beach, et al., 1992; McMaster & Troup, 1993). A five year epidemiological study of a Division I collegiate swimming program found the shoulder to endure the highest frequency of injury, to be the most recurrent body part to undergo surgery, and to be the most common reason for lost practice time in the injured swimmer (Wolf, Ebinger, Lawler, & Britton, 2009). While 80 percent of competitive events last under two minutes, optimal swimming performance is often preceded by a large amount of in-water training (Trappe, 1995). On average, swimmers at the collegiate level swim between 40,000 and 50,000 yards each week and an elite swimmer may complete 20,000 yards in one day (McMaster & Troup, 1993; Stocker, et al., 1995). The swim season lasts 10-12 months and competitive swimmers practice 5-7 days per week, often twice daily (Beach, et al., 1992). It is important to note that roughly 80 percent of a swimming practice is performed using the freestyle stroke (Beach, et al., 1992). Although there are four strokes in the sport of swimming (butterfly, backstroke, breast stroke, and freestyle), freestyle is performed most often by competitive swimmers so it were the main focus of this literature review and this study.

With high volumes of freestyle training, competitive swimmers average about 18,000 overhead shoulder revolutions per week (M. Pink, et al., 1991). Clearly, the swimmer's shoulder is subject to overuse injury through these common training trends, and it becomes only more vulnerable to injury when freestyle biomechanics are performed incorrectly at this frequency.

ETIOLOGY OF SHOULDER PAIN

"Swimmer's shoulder" is a general term frequently used to describe the shoulder pain or injury experienced by a competitive swimmer (McMaster, et al., 1998). The anatomy of the shoulder complex is prone to overuse injury, especially in athletes who participate in sports that use repeated overhead movements such as freestyle swimming (Starkey & Ryan, 2002). Common injuries causing shoulder pain can be reflected in a study of NCAA Division I overhead athletes, displaying high incidence rates of subacromial impingement, rotator cuff tendonitis, and biceps tendonitis among swimmers (Laudner & Sipes, 2009).

Shoulder Impingement

A compressive force on the subacromial structures occurs when there is contact between the greater tuberosity of the humerus and the acromial arch in the shoulder (Yanai, et al., 2000). The Neer test for diagnosis of subacromial impingement reproduces pain when the arm is forcibly flexed forward and the greater tuberosity of the humerus is pushed against the anterior-inferior surface of the acromion (Kennedy, Hawkins, & Krissoff, 1978). Forward flexion and internal rotation of the shoulder will also reproduce subacromial impingement and pain by driving the greater tuberosity of the humerus under the coraco-acromial ligament and onto the long head of the biceps tendon (Johnson, et al., 2003;

Kennedy, et al., 1978). Freestyle biomechanics and common stroke errors can often mimic these movements, exacerbating subacromial impingement and resulting shoulder pain(Kennedy, et al., 1978) Due to the structure of the shoulder girdle and the repetitive overhead revolutions used in freestyle, it is difficult for shoulder impingement to be avoided in front-crawl swimming. However, research shows swimmers who modify their stroke biomechanics to avoid the impinged position are able to decrease their occurrence of subacromial impingement (Yanai & Hay, 2000).

Rotator Cuff and Biceps Tendinopathy

Rotator cuff and biceps tendinopathy are common shoulder pathologies experienced by swimmers. Shoulder impingement occurring in the avascular region of the supraspinatus and biceps tendons can produce microtears in the tissue and focal cell death, which can create an inflammatory response such as tendinitis (Kennedy, et al., 1978). These tendons share a position directly under the coracoacromial arch which is formed by the coracoid process, the coracoacromial ligament, and the anterior acromion (Fowler, 1995). The repetitive overhead arm motion of freestyle swimming often causes the rotator cuff to be overworked and become fatigued as it attempts to stabilize superior migration of the humeral head in the glenoid fossa (Fowler, 1995). This can lead to a chronic condition and tendinopathy of the rotator cuff (Fowler, 1995). The biceps tendon originates from the glenoid tubercle, runs intra-articularly, and leaves the joint at the bicipital groove (Kennedy, et al., 1978). This tendon is often irritated by its repetitive impingement in the subacromial space, which can be caused by a flawed freestyle stroke.

Glenohumeral Instability

The shoulder displays great range of motion which is frequently achieved at the expense of joint stability (Starkey & Ryan, 2002). The glenohumeral joint exhibits shallow articular surfaces, has inconsistent ligamentous support, and an relies heavily on muscular support (Starkey & Ryan, 2002). Stability of this joint is essential for proper joint mechanics and without it the individual will experience significant disability and probable shoulder pathology (McMaster, et al., 1998). One study which evaluated 36 competitive swimmers with shoulder pain found that 21 of the subjects' shoulders had positive apprehension signs, suggesting that clinical glenohumeral instability is common among these athletes (Bak & Fauno, 1997). High volumes of freestyle training in which the rotator cuff is overused may contribute to microtrauma and impingement, leading to this shoulder instability (Allegrucci, Whitney, & Irrgang, 1994). Many swimmers exhibit general shoulder joint laxity that occurs at first as increased range of motion (McMaster, et al., 1998). Likewise, a significant correlation between glenohumeral joint laxity and the presence of interfering shoulder pain in swimmers has been reported (McMaster, et al., 1998). What is more, as this laxity increases, glenohumeral instability and exacerbated shoulder pain may develop (McMaster, et al., 1998). One study which compared normal shoulders and shoulders with glenohumeral instability showed that 68 percent of patients with instability had significant impingement signs in addition to apprehension and capsular laxity, which produces an overall increased potential for shoulder pain (Warner, Micheli, Arslanian, Kennedy, & Kennedy, 1990).

FREESTYLE STROKE BIOMECHANICS

Through the analysis of freestyle stroke biomechanics, the front crawl arm pattern can be broken down into a classification system of phases. The freestyle stroke can be organized through the stroke segments of below-water and above-water phases and can be further classified into hand entry, the pull-through phase, and the recovery phase (McMaster & Troup, 1993; M. Pink, et al., 1991; Yanai & Hay, 2000). Swimming technique has concentrated more on performance increases, and has less often focused on biomechanical advancements to contend with the vigorous demands placed on the swimmer's shoulder. Coaching literature on swimming biomechanics has typically been based on the results from practical coaches and talented athletes learning through trial and error (Colwin 2002).

Improper Swimming Biomechanics

Swimming with improper freestyle mechanics has been suggested by both researchers and coaches as a dominant risk factor for shoulder pathology and pain (Johnson, et al., 2003; Kennedy, et al., 1978; M. M. Pink & Tibone, 2000; Prins, 2009; Scovazzo, et al., 1991; Wilk, et al., 2009; Yanai & Hay, 2000). A biomechanics study focusing on shoulder impingement in the front crawl has shown male collegiate swimmers are in an impinged position, where there is contact between the greater tuberosity of the humerus and the acromial arch as well as stress on the structures in this space, for about 25 percent of their freestyle stroke time (Yanai & Hay, 2000; Yanai, et al., 2000). This illustrates that even swimmers employing an unflawed freestyle stroke will experience a moderate amount of shoulder impingement. However, swimming with a freestyle stroke that includes biomechanical errors is thought to increase the time spent in the impingement position and often cause undesirable shoulder problems. For example, freestyle stroke errors such as improper hand entry, dropped elbow, and excessive adduction during the pull-through phase have been found to place stress on the subacromial shoulder structures and have the potential to create shoulder pain (Johnson, et al., 2003; Scovazzo, et al., 1991; Wilk, et al., 2009;

Yanai & Hay, 2000). A stroke biomechanics assessment is important for all competitive swimmers to help identify contributors to existing and potential pain. While swimming with improper stroke mechanics has been established as a risk factor for shoulder pain and injury, a clear correlation between faulty freestyle stroke technique and shoulder pain has yet to be identified through biomechanical research.

However, there have been several evidence based studies in which freestyle biomechanics and front crawl muscle activation have been examined, identifying stroke errors as potential risk factors for shoulder pain in competitive swimmers (M. Pink, et al., 1991; Scovazzo, et al., 1991; Wilk, et al., 2009; Yanai & Hay, 2000). A summary of these errors is included in **table 1**.

Hand Entry

During the freestyle stroke, the hand should enter the water forward and lateral to the head, but remain medial to the shoulder (M. Pink, et al., 1991). Text by experienced swimming coaches stresses the importance of arm and hand positioning during this phase, aiming to increase the propulsive forces gained through correctly executed freestyle stroke biomechanics and place the body in a more streamlined position (Colwin, 2002). The elbow should be flexed and the fingers or little finger should enter the water first (M. Pink, et al., 1991). Peak activity of the anterior and middle deltoid, rhomboids, upper trapezius, and supraspinatus occur during this phase as well (M. Pink, et al., 1991). Normal muscle activation throughout the stroke phases will aid in the execution of correct stroke biomechanics, thus leading to less biomechanical errors and decreasing the potential for shoulder pain in swimmers.

Freestyle stroke errors that occur during the hand entry are suggested to be contributors to shoulder pain in the competitive swimmer. A hand entry that occurs further away from the midline or crosses the body axis is an example of stroke error during this phase (Scovazzo, et al., 1991). This increases the amount of time the shoulder spends in an exaggerated impingement position (Johnson, et al., 2003). This position also mimics the Neer shoulder impingement testing position which would create pain in a swimmer with symptomatic shoulders (Wilk, et al., 2009). A thumb-first freestyle hand entry instead of a fingers or pinky-first hand entry is thought to increase stress at the long head of the biceps attachment to the anterior labrum (Johnson, et al., 2003).

Pull-Through Phase

This phase begins after the hand enters the water and ends following the underwater pull as the hand leaves the water (M. Pink, et al., 1991). The shoulder begins in forward flexion, abduction, and internal rotation during early pull-through and finishes in adduction and internal rotation as the palm approaches the thigh to exit (M. Pink, et al., 1991; Wilk, et al., 2009). A straight back pull-through pattern is suggested as correct biomechanics for the freestyle stroke during this phase of freestyle (Colwin, 2002; Johnson, et al., 2003). This produces a more natural sculling in which the arms will move inward and outward slightly and cause the body to rotate (Colwin, 2002). It is recommended that during pull-through the elbow is kept higher than the hand, pointing laterally, and reaching its maximum bend halfway through the pull (Colwin, 2002).

Incorrect mechanics during the pull-through phase of freestyle can give rise to shoulder pain in the competitive swimmer. Dropping the elbow during this phase places the propulsive muscles of the shoulder at a mechanical disadvantage by increasing shoulder external rotation and stress on the joint (Richardson, et al., 1980). This stroke error is one that is commonly identified by swimming coaches and can result in large shoulder external rotation with horizontal adduction (Yanai & Hay, 2000). An incorrect S-shaped pull-through pattern mimics the Hawkins Kennedy impingement testing position of shoulder horizontal adduction, flexion, and internal rotation, increases the time spent in the impinged position, and can lead to adverse shoulder pain in the swimmer (Johnson, et al., 2003; Wilk, et al., 2009; Yanai & Hay, 2000). The pull-through phase ends as the hand leaves the water which then begins the recovery phase (M. Pink, et al., 1991) .

Recovery Phase

This phase takes place above the water and ends just before hand entry occurs (M. Pink, et al., 1991). An early hand exit just above the belt line has been encouraged to help the swimmer avoid time spent in the impingement position (Johnson, et al., 2003). The hand exit and early recovery should be smooth and controlled to eliminate a decrease in momentum (Colwin, 2002). Most importantly, the elbow should be kept higher than the wrist throughout the recovery phase and should avoid a dropped elbow position during this above water phase (Colwin, 2002; Wilk, et al., 2009). An appropriate amount of body roll must be achieved during the recovery phase of freestyle. As one arm pulls, the shoulders, hips, and legs all gradually rotate simultaneously to change the swimmer's body alignment and maintain momentum in the water (Colwin, 2002). A body roll angle of at least 45° along the longitudinal axis of the body has been suggested to facilitate correct stroke pattern (Johnson, et al., 2003).

Biomechanical errors during the recovery phase may be both contributors and indicators of shoulder pain. The differences in stroke biomechanics seen in a healthy and painful shoulder sometimes occur due to a swimmer's attempts to avoid the painful impingement positions of the freestyle stroke. As the swimmer lifts the arm out of and over the water's surface during the recovery phase, there is a collision of the rotator cuff under the acromion, which resembles the Hawkins-Kennedy impingement test and swimmers with shoulder pain may try to avoid this position through technique modifications (Bak & Fauno, 1997; Scovazzo, et al., 1991). Stroke errors such as a dropped elbow may be occurring to make the humerus more perpendicular to the water, produce a shorter arc of motion, and decrease time spent in in an impinged position (Scovazzo, et al., 1991). This stroke alteration is considered incorrect but may be indicative of a swimmer who is attempting to avoid the classic impingement position of shoulder flexion and internal rotation (Scovazzo, et al., 1991). It is possible that this error seen in swimmers could be the consequence of pain and not the cause, however this is not known. Dropped elbow, nevertheless, will lead to an improper entry position with the elbow entering before the hand, and thus exacerbate biomechanical errors and resulting shoulder pain further in the stroke pattern (Wilk, et al., 2009). The water will cause an upward force on the dropped humerus, leading to its superior translation and subacromial impingement in the shoulder (Wilk, et al., 2009). Additionally, a body roll angle that does not fall near the recommended 45° of rotation can lead to shoulder pain as it contributes to the development of errors further in the stroke cycle. Excessive body roll angle can initiate crossover entry position during both the recovery and pull-through phases and create impingement in the shoulder (Johnson, et al., 2003). Conversely, a lack of body roll during the recovery phase can increase mechanical stress on the shoulder, leading to improper hand entry position with a large angle of shoulder elevation and increased compressive forces of the subacromial shoulder structures (Johnson, et al., 2003; Yanai & Hay, 2000). It has been suggested that a swimmer can reduce this painful angle of elevation by increasing their amount of body rotation (Yanai & Hay, 2000).

Lastly, the head carrying angle should remain constant throughout each phase of the stroke when a swimmer is not breathing. A neutral head position where the swimmer's eyes are looking toward the bottom of the pool is recommended (Johnson, et al., 2003). When performing a correct head carriage position, the swimmer should feel as though a straight line could be drawn from the top of the center of their head through their spine (Johnson, et al., 2003). On the other hand, an eyes-forward head carrying angle during freestyle is considered incorrect biomechanics and is thought to increase shoulder impingement as it hinders normal scapulothoracic motion (Johnson, et al., 2003).

TECHNIQUE ANALYSIS IN BASEBALL PITCHERS

A study performed on youth baseball pitchers examined the relationship between common biomechanical errors in pitching mechanics and joint stress in the upper extremity (Davis et al., 2009). This study used motion and video analysis to look at flaws in pitching technique and demonstrated the injury risk associated with these errors. The results of the research found that youth pitchers using improper mechanics generated higher joint stresses in their elbows than those who pitched with correct mechanics (Davis, et al., 2009). This proved to quantify the effect that common pitching errors have on joint stress and pitching efficiency (Davis, et al., 2009). Such information allows coaches and Athletic Trainers to work together to identify errors in pitching kinematics, thus providing scientifically based pitching instruction that can decrease injuries in the upper extremity. Based on these findings, one can hypothesize that swimmers who exhibit a high number of biomechanical errors in their freestyle stroke will have a related shoulder pain score indicating high shoulder pain.

INSTRUMENTATION

This study utilized underwater and above water cameras to capture the freestyle biomechanics of participating competitive swimmers. Two Underwater Camera Company of America's CoachCams® underwater video capture systems were used to film the underwater freestyle biomechanics of each subject. Two Sony HDR-XR150 120GB High Definition HDD Handycam camcorders (Sony Corporation of America) with input/output functions were used in conjunction with the Coach Cam® underwater cameras to film the above water stroke patterns of each swimmer. The swimmers' strokes were captured from the frontal and sagittal plane angles, using four synchronized cameras which were positioned both under and above the water. A similar video analysis protocol has been used to successfully examine the arm coordination, power, and swim efficiency of front crawl swimmers (Seifert, Toussaint, Alberty, Schnitzler, & Chollet, 2010).

Dartfish® TeamPro Video Analysis Software

The underwater video was analyzed through Dartfish® TeamPro video analysis software. Each camera captured different parameters of the swimmer's stroke which were observed via the Dartfish® software. The Dartfish® software allowed for the video clips to be synchronized and had the capabilities to replay video at different speeds, play video forward and backward, zoom in and out, magnify video clips, and had picture-in-picture ability. A previous study on technical alterations in freestyle technique during time-to-exhaustion tests has used Dartfish® TeamPro software to analyze the arm-stroke cycles of 10 well-trained swimmers (Alberty et al., 2008). In addition, anecdotal evidence from discussions with local club and college coaches indicated that the Dartfish® software is commonly used by teams for stroke analysis.

The Penn Shoulder Score

The Penn Shoulder Score was used to calculate pain scores for each subject's left and right shoulders (**Appendix 1**). This self-report questionnaire included a pain, satisfaction, and function subscale (Leggin et al., 2006). The Penn Shoulder Score has been demonstrated to be a valid and reliable measure for reporting shoulder pain in patients with various shoulder disorders (Leggin, et al., 2006).

DASH Outcome Measure

The Disabilities of the Arm, Shoulder and Hand (DASH) Outcome Measure is a self-report questionnaire which examines function and symptoms in patients who are experiencing musculoskeletal disorders of the upper limb. Subjects will also receive two copies of the DASH Outcome Measure to complete for both their right and left shoulders. The DASH is scored through two sections. The DASH Sport Module, which identifies difficulties athletes may experience while performing their specific activity, will also be included in the subjects' materials to help appropriately gauge their shoulder pain levels.

SUMMARY

It is important to recognize errors in freestyle biomechanics and their contribution to shoulder pain in swimmers. If a joint fails to move correctly, an injury will occur at the site (Houglum, 2005). With intense training trends and common physical characteristics already predisposing swimmers to an array of shoulder problems, swimming with improper biomechanics may further increase the risk of shoulder injury. Gaining a better understanding of flawed freestyle biomechanics and resulting shoulder pain could allow for recommendations to be made to guide future studies and decrease the influence of this threat to shoulder injury. Athletic Trainers and swimming coaches are in need of an established assessment tool for freestyle technique observation to help minimize the detrimental consequences of incorrect shoulder function during swimming. In order to have a complete understanding of shoulder motion during freestyle swimming and its relationship to shoulder pain, research on front crawl biomechanics and associated shoulder pain is needed. Clinicians treating this population can use the information in this study as an approach to injury prevention in the swimming athlete, decreasing the occurrence of debilitating shoulder pain which commonly plagues competitive swimmers.

CHAPTER III

METHODOLOGY

PARTICIPANTS

Sixty local club swimmers were asked to participate for this study. Swimmers were both males and females between the ages of 15 and 25 years old. This age range will include both senior level club swimmers and collegiate level swimmers from the club swimming team. The primary investigator will meet with all potential subjects and explain the project. Those interested in participating were provided informed consent and enrolled in the study.

SUBJECT INCLUSION CRITERIA

Subjects were included in the study if they meet all of the following criteria:

- Regularly train at least 5 times per week, 1-2 hours each practice session
- Has had at least 5 years competitive swimming experience. Competitive swimming experience must have been obtained as a member of a club, YMCA, or high school swimming team
- Is currently completing practice with no restrictions at the time of the filming

SUBJECT EXCLUSION CRITERIA

Subjects were excluded from this study if:

- They were unable to complete practices fully due to pain, injury, or illness at the time of the testing session

INSTRUMENTATION

Two CoachCam® underwater video capture systems (Underwater Camera Company of America, Alpine, CA) were used in this study to film the underwater stroke patterns of each swimmer. Additionally, two Sony HDR-XR150 120GB High Definition HDD Handycam camcorders (Sony Corporation of America) with input/output functions were used adjunct to the Coach Cam® underwater cameras to film the above water stroke patterns of each swimmer. One of the CoachCam® underwater cameras was secured on the end of a telescopic pole, which allows positioning of the camera at the appropriate depth while filming. This CoachCam® remained stationary and captured an underwater lateral view of the swimmers' stroke patterns. One of the Sony camcorders was positioned on a stationary tripod for capturing lateral view above water film. This camera view was adjusted to capture the last 15 yards of the pool. A second CoachCam® underwater camera was secured to a metal pole at the far end of the swimming pool, capturing the underwater frontal view film of the swimmers. This pole hung from the swimming pool gutter and dropped into the water, resting flat against the side of the wall. The second Sony camcorder was positioned on a stationary tripod at the end of the pool to capture the swimmers' above water stroke patterns from the frontal view. Both underwater cameras were wired to their own monitoring screen (Vizio E420VO 42-Inch 1080p LCD HDTV) which have Dartfish® software capabilities.

Dartfish® TeamPro video analysis software (Dartfish USA, Inc.) was used to organize, clip, and view the recorded film of each subject's freestyle biomechanics. Dartfish® software uses live video recording at 60 frames per second to help with the analysis of each freestyle stroke. The software had the capabilities to replay video at different speeds, play video forward and backward, zoom in and out, magnify video clips, and has picture-in-picture ability. All of these functions were utilized during the clipping of film and film evaluation.

The Penn Shoulder Score was used to calculate pain scores for each subject's left and right shoulders (**Appendix 1**). It was scored out of 100 total points with 30 possible points representing the subject's pain, 10 possible points regarding shoulder satisfaction, and 60 possible points representative of their shoulder function. A lower total score was indicative of greater shoulder pain and disability among the subjects. The Penn Shoulder Score's use of three separate subscales allowed swimmers to rate their shoulder function and shoulder satisfaction, both of which are important and commonly reported to swimming coaches and swimming Athletic Trainers when shoulder pain is present. This survey also forms a total score to encompass magnitude of shoulder pain at rest, during activities of daily living, and during strenuous activities, providing a thorough history to summarize each subject's status. This study utilized the total score calculated from the addition of all subscales. The Penn Shoulder Score has been demonstrated to be a valid and reliable measure for reporting shoulder pain in patients with various shoulder disorders (Leggin, et al., 2006).

PROCEDURES

Informed consent approved by the University of North Carolina at Chapel Hill Institutional Review Board was obtained from all participants prior to the study. All swimmers signed consent forms immediately prior to the testing session. For subjects age 15-17, consent from the parent or guardian was also obtained prior to testing. Prior to testing, subject's demographics and information on the swimming experience (sex, height, weight, years of swimming experience, and current event specialization of each participating swimmer) were obtained. The Penn Shoulder Score self-reporting questionnaire was also completed by each participant immediately prior to the swimmers' participation in the study trials. Each swimmer completed one Penn Shoulder Score questionnaire for their right shoulder and one questionnaire for their left shoulder. It was scored out of 100 total points with 30 possible points representing the subject's pain, 10 possible points regarding shoulder satisfaction, and 60 possible points representative of their shoulder function. Based on the swimmers' responses, each of these three subscale scores were combined for a composite shoulder pain score out of 100 possible points. A lower total score was indicative of greater shoulder pain and disability. These shoulder pain scores were used in data analyses.

Swimmers were also asked to rate their shoulder pain on a scale of 1 through 10. This was completed by circling a number that best matched their pain sensation prior to filming, and then again after filming. When the swimmers rated their pain following participation in the filming, they were asked to recall the pain experienced during the trials and rate it accordingly on the pain scale. This was done for both the left and right shoulder of each subject.

Filming of Freestyle Biomechanics

Swimmers were recorded for 2 trials while swimming freestyle to capture both the right and left sides of the athlete. Filming occurred on a day where the subjects did not have a regular practice. Each swimmer was asked to perform at least 100 yards of freestyle to warm up. Filming took place over several days within two consecutive months in the regular competitive season, but each swimmer only completed the trials one time. The collegiate level participants completed testing over the same month of the competitive season. It was planned that senior level club swimming participants would complete testing prior to their practice during these same months, however equipment problems hindered the primary investigator's ability to include these subjects in the study. All trials were performed in a 25-yard indoor swimming pool where the team normally trains. Prior to filming, all lane lines surrounding the filming area that may have obstructed the camera's views were removed. Subjects performed trials in lane 2 of an 8 lane competition swimming pool. Lane 2 was an appropriate distance of approximately 15 feet from the lateral view cameras and allowed for the best video capture angle. The following filming parameters were used based on a protocol similar to that of a previous swimming biomechanics study (Seifert, et al., 2010). All video cameras began filming at the same time to synch each individual swimmer's stroke pattern throughout the different camera angles. One underwater and one above-water camera were placed at the end of a 25-yard swimming pool to obtain frontal views of each swimmer's freestyle biomechanics. The frontal view underwater camera was fixed on the edge of the pool 0.4m below the surface of the water. The above-water camcorder filmed from a stationary tripod on the pool deck and captured the frontal view of each swimmer's above-water stroke pattern. The lateral view was obtained from both the underwater and above water cameras. The underwater camera was secured on to the telescopic pole that was held stationary by the operator who is standing on deck. The Sony handheld camcorder was positioned on a stationary tripod set at the appropriate height and distance to capture the necessary filming area. Both lateral camera views were adjusted to capture the last 15 yards of the pool. This view encompassed the observable 15 yard and 5 yard lane rope markers, which were used to help guide the video clipping process. The camera set up is illustrated in **Figure 8**. Both underwater cameras were connected to their own monitoring screen to record the frontal and lateral views in Dartfish®. The above water camcorder film was uploaded to a computer by the primary investigator for analysis in Dartfish®.

Each swimmer was instructed to swim freestyle for 25 yards (one length of the swimming pool) at a pace 50-75 percent of their maximum race speeds, using their natural stroke technique. Swimmers were asked to refrain from breathing for the last 15 yards of the pool while passing the lateral view cameras. These instructions were provided to avoid stroke alterations due to increased body rotation that occurs during breathing. During trial 1, the subject swam 25 yards freestyle. Trial 2 occurred immediately following trial 1. During trial 2 the subject swam 25 yards freestyle, this time swimming in the opposite direction. Swimmers began each trial in the water from a basic wall push-off. A lateral view of the swimmer's left side was obtained during trial 1. The swimmer was then asked to repeat this method for trial 2 in the opposite direction, swimming freestyle for 25 yards from a wall push-off. Swimmers were asked to minimize their underwater streamline from push-off to 5 yards so that they were swimming freestyle as they pass the lateral view underwater camera. A lateral view of the swimmer's right side was during trial 2. The frontal view cameras moved from one end of the pool to the other between trials. This allowed the left arm frontal view to be captured and synchronized with the left arm lateral view during trial 2. Video from all cameras was started and stopped between subjects to allow for the primary investigator to label the video clip with an identification number for each individual swimmer.

Cycle Selection and Film Clipping

Following all filming of trials, the primary investigator selected a stroke cycle for grading and clipped the films. The investigator identified and labeled the trials by subject identification number. A master list was kept and saved with each subject's ID number to maintain confidentiality of participants. Identification numbers were recorded for each trial for additional subject identification during video analysis.

A stroke cycle was considered for analysis if the hand entry, pull-through, and recovery phase were clearly visible in the combined underwater and land views of each camera when viewed in Dartfish® following filming. The primary investigator viewed all camera angles. One complete stroke cycle was selected for each swimmer and each trial from a combination of each of the camera views. The hand entry position clip was selected from the above water frontal angle video. This clip encompassed the recovery phase until the beginning of the pull-through phase. The pull-through phase, body roll, and head carrying angle clips were selected from the underwater frontal camera angle video. The recovery phase and hand entry angle clips were selected from the above water lateral view film. The recovery phase video clip began when the hand started the above-water phase of the stroke and it ended following the subject's hand entry into the water. The pull-through phase was selected from the underwater lateral view camera film. This clip began when the subject's hand entered the water and lasted until the swimmer's palm approached the thigh. Yanai and Hay (Yanai & Hay, 2000) described parameters for which a stroke cycle can be selected during video analysis. These parameters included 1) the cycle must be completely within the camera view, 2) the periscopes and underwater cameras must have captured the subject sufficiently well so that his/her body was positioned at the center of each field throughout filming, and 3) the image size of the subject projected on the monitor must be large enough to be viewed in the Dartfish® software. The first full stroke cycle to enter the camera view and meet the previous criteria were selected for evaluation. The primary investigator ensured that the same stroke cycle was clipped using video synchronization of the underwater cameras via the Dartfish® software and visual guidance from the 15 yard and 5 yard lane rope markers on the above water camera film. Pilot testing of the filming protocol occurred prior to the study.

Grading of Biomechanics

Two experienced swimming coaches and one Certified Athletic Trainer who have had experience working with the collegiate-level swimming team and had no knowledge of the swimmers' shoulder injury histories or freestyle strokes were asked to observe and evaluate the selected video clips of each subject's freestyle biomechanics. All 3 evaluators reported to the Koury Natatorium conference room at the University of North Carolina Chapel Hill for grading of video analysis on a selected date following filming and clipping of all subjects' freestyle stroke cycles. All examiners underwent standardized guidance through the use of still photographs of the 7 biomechanical parameters and sample video examples freestyle biomechanics prior to the evaluator reviewing the selected freestyle stroke cycles of each swimmer. The 7 parameters considered to be common errors of freestyle were explained to the observers by the primary investigator. Each error was described in relation to the phase of the freestyle stroke (hand entry, pull-through, or recovery) in which it occurs. Evaluators were allowed to discuss their opinions of the biomechanical parameters presented in the training photos and videos among each other and with the primary investigator. This served as a practice evaluation before the actual test trial videos were presented to the group. The following parameters were applied to the right and left arm of each swimmer:

(a) Hand Entry

(i) Correct biomechanics **(Figure 1 A):** Fingers-first or little finger-first entry(Johnson, et al., 2003; M. Pink, et al., 1991)

(ii) Incorrect biomechanics **(Figure 1B):** Thumb-first entry(Johnson, et al., 2003)

(iii) Correct biomechanics **(Figure 2A):** Hand enters lateral to head and medial to shoulder(M. Pink, et al., 1991)

(iv) Incorrect biomechanics **(Figure 2B):** Hand crosses the long axis midline of the body or is placed lateral to shoulder at entry (Johnson, et al., 2003; Scovazzo, et al., 1991)

(b) Pull-through

(i) Correct biomechanics **(Figure 3A):** Straight back pull-through(Colwin, 2002; Johnson, et al., 2003)

(ii) Incorrect biomechanics **(Figure 3B):** S-shaped pull-through or excessive horizontal adduction during pulling(Johnson, et al., 2003; Wilk, et al., 2009; Yanai & Hay, 2000)

(iii) Correct biomechanics **(Figure 4A):** Elbow kept higher than wrist, pointing laterally, reaching maximum bend at half-way through pull(Colwin, 2002)

(iv) Incorrect biomechanics **(Figure 4B):** Dropped elbow (Richardson, et al., 1980)

(c) Recovery

(i) Correct biomechanics **(Figure 5A):** Elbow kept higher than wrist throughout the phase(Colwin, 2002; Wilk, et al., 2009)

(ii) Incorrect biomechanics **(Figure 5B):** Dropped elbow(Richardson, et al., 1980; Wilk, et al., 2009)

(iii) Correct biomechanics **(Figure 6A):** Body roll of 35-45° occurs along the longitudinal axis of the body (Colwin, 2002; Johnson, et al., 2003)

(iv) Incorrect biomechanics **(Figure 6B):** Excessive or lack of body roll angle (Johnson, et al., 2003)

(d) Not phase-specific

(i) Correct biomechanics **(Figure 7A):** Head in neutral position (Johnson, et al., 2003)

(ii) Incorrect biomechanics **(Figure 7B):** Head carriage is in eyes forward position (Johnson, et al., 2003)

After all questions had been answered and the primary investigator determined that the evaluators understood the parameters, grading of the videos began. Each evaluator was provided with a form to evaluate the biomechanical errors for each subject (**Appendix 2**). Film was viewed simultaneously by the three evaluators on an overhead projector. The primary investigator verbally identified which arm the observers should focus their attention on for each video clip. Film for each swimmer was presented at 25% speed, as many times as needed for the evaluators to best observe the video clip. Film speed was permitted to be increased or decreased at the request of an evaluator. The primary investigator started and stopped the film between each subject and each trial. Additional guidance or feedback regarding the primary investigator's opinions of the filmed biomechanics was not provided. However, the primary investigator was able to reiterate the designated incorrect and correct biomechanical parameters defined previously on request of the evaluators. Evaluators were able to ask the investigator to replay a phase or parameter view but they were not permitted to ask to return to a previous swimmer's trial once grades had been finalized for that participant. Evaluators were blinded to the other evaluators' grades during the process. The right and left arms of each subject were evaluated independently, thus a total error score was provided for the left and right side of each swimmer. Each of the 7 parameters was graded as a *yes* or *no* by each evaluator after reviewing the selected stroke cycle from all camera angles. For example, if a swimmer displays a hand entry position of a thumb-first entry on their left arm, the observer should have rated it as a *yes*, indicating that the swimmer was performing incorrect biomechanics for this parameter on their left side.

Reliability of the evaluation criteria for specific biomechanical errors and total error scores was examined. The primary investigator graded a sample of 10 subjects' film on two separate occasions. The kappa values for each specific error were determined by examining the agreement between grades from both evaluation sessions. The Spearman correlation coefficient was used to assess the relationship between total error scores from both evaluation sessions. Kappa values were 0.615 or greater for all seven specific freestyle biomechanical errors in question. There was a positive correlation between total error scores from both evaluation sessions ($r = 0.934$, $n = 20$, $p = .000$). Overall, this evidence supports strong intra-rater reliability among multiple grading sessions performed by a single evaluator. These reliability statistics are located in **Table 5**.

DATA REDUCTION

Following the video evaluation session, the observers submitted their grading forms to the primary investigator who determined the final grade for the presence of an error based on the responses. A "majority rules" method was used, in which the most common response between the three observers was used for the determination of each biomechanical parameter. For example, if two evaluators graded a parameter as *yes* and one evaluator graded that same parameter as *no*, the parameter would have been rated as a *yes* for displaying the biomechanical error. A total error score was calculated from the final evaluations of the biomechanical parameters as the sum of the *yes* responses for each side. The total error score was calculated for both the right and left sides of each swimmer. The lowest total error score an individual could receive per side was 0 out of 7 errors while the highest error score they could receive was 7 out of 7 errors. These final scores were used in data analyses.

STATISTICAL ANALYSIS

A logistic regression was performed to determine if the total error score (the number of freestyle biomechanical errors) predicts the pain score in elite competitive swimmers. A step-wise multiple logistic regression were performed to examine the specific biomechanical parameters that most significantly predict shoulder pain scores in elite competitive swimmers. An a priori alpha level of 0.05 were set. Statistical analyses were run using SPSS version 19.0 (SPSS Inc., Chicago, IL). Power analysis indicates that 60 subjects were needed, however data on only 31 subjects was able to be collected.

CHAPTER IV

RESULTS

Thirty-one subjects participated in this study. Therefore, film of freestyle biomechanics, Penn Shoulder Pain Scores, and biomechanical error evaluation were collected for sixty-two independent shoulders. Subjects were competitive swimmers who were between 18 and 24 years old and had been swimming competitively for at least five years. Subjects' average age, height, and mass were 20 years old ± 1.41, 179.1716 cm ± 9.65, and 75.43 kg. ± 8.64, respectively. On average, participants had swum competitively for 11.3 ± 3.49 years. This information is presented in **Table 2.**

FREESTYLE BIOMECHANICAL ERRORS

While seven freestyle stroke biomechanical errors were originally examined in the evaluation process, kappa statistics were calculated to provide a measurement of reliability and precision between the evaluators' grades to determine which variables would be added into the regression equation. Variables with a kappa agreement value greater than 0.30 were included in the analysis, while variables below this value were excluded. A kappa agreement (< 0.30) was found between evaluators' grades for the errors of excessive or lack of body roll (kappa = 0.012) and dropped elbow during the pull-through phase (kappa = 0.293). Therefore, these two errors were excluded from further statistical analyses because of their poor reliability. Kappa agreement statistics for the remaining errors were kappa = 0.317 or above and therefore were included in the regression equation. Kappa statistics for the evaluator agreements of each biomechanical error are presented in in **Table 3.** The distribution of specific errors observed among the subjects was somewhat related to the kappa agreement statistics. While evaluators felt only 17 out of 62 shoulders displayed improper amounts of body roll during the stroke cycle, there was also a poor agreement of 0.012 among their grades. It is possible that the low number of subjects evaluated as displaying this error was related to the poor evaluation agreement, which may have stemmed from unclear definitions of biomechanics or unclear camera views. A distribution of the subjects displaying specific errors as well as a graph encompassing the range of total error scores can be found in **Figure 10** and **Figure 11**, respectively.

While the intra-rater reliability determined by the primary investigator's multi-session evaluation grades was strong, these kappa agreements reveal low homogeneity among the three evaluators and poor inter-rater reliability. This information suggests the evaluation criteria may need refined or the raters may have needed to be trained differently prior to the final evaluation process.

PENN SHOULDER SCORE AND RELATIONSHIP WITH BIOMECHANICAL ERRORS

A multivariate linear regression was performed to determine if the total number of technique errors predicted PENN Shoulder Score. The results of the regression indicate that the total error score explained 0% of the variance in the PENN shoulder score ($R^2 = 0.00$, $F_{1,60} = 0.006$, $p = 0.936$). The total number of biomechanical errors was not predictive of the PENN shoulder score.

Additionally, a multiple linear regression was used to evaluate if specific biomechanical errors could significantly predict PENN shoulder pain score in competitive swimmers. The enter method was used in order to force all variables into the regression equation simultaneously. The results of the regression indicate that the specific biomechanical errors explain only 6.5% of the variance ($R^2 = 0.065$, $F_{5,56} = 0.782$, $p = 0.567$). None of the specific biomechanical errors significantly predicted the PENN shoulder pain score. The measurement of contribution of each specific freestyle stroke error to shoulder pain is expressed through the following results: thumb-first hand entry angle ($\beta = -0.076$, $p = 0.602$), incorrect hand entry position ($\beta = -0.150$, $p = 0.349$), S-shaped pull-through pattern ($\beta = 0.205$, $p = 0.145$), dropped elbow during recovery ($\beta = 0.234$, $p = 0.136$), and eyes forward head carrying angle ($\beta = -0.122$, $p = 0.389$). This data is presented in **Table 4.**

CHAPTER V

DISCUSSION

The purpose of this study was to examine the relationship between freestyle stroke biomechanical errors and shoulder pain in elite competitive swimmers. While it has been suggested that faulty freestyle stroke mechanics may precede shoulder pain, there is still an unclear correlation between the two variables within swimming literature. Although no relationship between flawed technique and shoulder pain was found, this research was conducted with an aim to help swimming coaches and Athletic Trainers who work in the competitive swimming population better identify errors in freestyle stroke biomechanics and to aid in injury prevention in the competitive swimming athlete.

FREESTYLE BIOMECHANICAL ERRORS AND SHOULDER PAIN

While there were no statistically significant findings which indicated a relationship between shoulder pain scores and the presence of freestyle biomechanical errors, it is important to note that only 6.5% of the variance was explained by the specific biomechanical errors. This indicates that there may be other factors which are influential in shoulder pain scores. This study was performed to verify that the theorized correlation between freestyle biomechanical errors and shoulder pain is factual. Based on several previous studies evaluating freestyle stroke biomechanics, stroke errors have been assumed to be potential risk factors for shoulder pain in competitive swimmers

(Johnson, et al., 2003; Scovazzo, et al., 1991; Wilk, et al., 2009; Yanai & Hay, 2000). It has been found that swimmers are subject to shoulder impingement for about 25% of their freestyle stroke cycle when using proper biomechanics (Yanai & Hay, 2000). It has been proposed that the amount of time spent in an impingement position would likely increase with improper freestyle technique. Therefore, the presence of freestyle biomechanical errors has been thought increase the time in which the subacromial structures are impinged during front crawl swimming, stress the anterior shoulder, and contribute to shoulder pain and pathology (Johnson, et al., 2003; Wilk, et al., 2009; Yanai & Hay, 2000; Yanai, et al., 2000).

While the biomechanical factors included in this regression had the strongest theorized evidence in the literature and were presumed to be most easily observable to the human eye, they were not predictive of shoulder pain. However, there are other elements of the freestyle stroke that may also contribute to the development of shoulder pain. For example, subjects were asked not to breathe while in the camera view because this would have compromised the ability to evaluate the technique errors that we intended to evaluate. Unilateral breathing in subjects without shoulder pain has been associated with a small magnitude of scapular tilt angle, increased shoulder impingement on the ipsilateral side, and therefore increased likelihood of shoulder pain development (Yanai & Hay, 2000). These filming instructions eliminated a biomechanical factor which could have shown a possible relationship to shoulder pain.

Also, flutter kicking rhythm typically alters arm coordination and would therefore be a potential biomechanical factor responsible for shoulder pain. A six-beat kick, most often used by sprinters and mid-distance swimmers, includes six kicks, or beats, per freestyle stroke cycle (Maglischo, 2003). The timing has been shown to contribute to the propulsive force during each freestyle underwater arm sweep and can reduce rates of deceleration during the freestyle pull-through (Maglischo, 2003). On the other hand, a two-beat kick rhythm, used mainly by distance swimmers, requires less energy expenditure but forces swimmers to modify their arm stroke timing. These swimmers usually utilize a quick catch and shorter downsweep during the pull-through phase, altering their freestyle stroke biomechanics to compensate for the lack of kick propulsion (Maglischo, 2003). Furthermore, swimmers with a weak kick, regardless of the rhythm, would need to accelerate their stroke rate which will likely increase overall number of overhead strokes taken per length of the pool. Analyzing each subject's flutter kick rhythm may provide insight into stroke pattern variations, and related shoulder pain.

Overall timing and synchronization of the arms and legs during the freestyle stroke may also be important to analyze when studying swimming biomechanics in relation to shoulder pain. Entering the recovery arm into the water too early or too late can force a swimmer to alter their pull-through stroke pattern by making their insweep shorter or wider, and potentially placing the shoulder in a vulnerable impingement position (Maglischo, 2003). Shortening their stroke and beginning the pull-through too soon will reduce the propulsion created by a swimmer's previous stroke, and likely increase loads place on the shoulder muscles of the pulling arm. Oppositely, a stroke that extends too long will occur if the swimmer's arm enters the water and lingers in front of them before beginning the downsweep of the pull-through phase (Maglischo, 2003). Not only does this reduce a swimmer's average velocity per stroke, but it increases the shoulder's time spent in an unfavorable position which simulates Neer's test for subacromial impingement. Timing and coordination of the arm cycle during freestyle may serve as an additional important biomechanical element to examine if a similar study were to be conducted.

In addition to biomechanical errors during training, there may be other participation factors related to the development of shoulder pain. A competitive season which lasts 10-12 months, and practices which occur 5-7 days per week, will lead to high volumes of training (Beach, et al., 1992). On average, swimmers at the collegiate level train between 40,000 and 50,000 yards per week, logging up to 20,000 yards in one day (McMaster & Troup, 1993; Stocker, et al., 1995). Coaches believe that successful performance in competitive swimming requires a combination of endurance and power, which is developed through these high loads of swimming. However, swimmers who undergo large amounts of training, specifically greater than 15 hours of swimming per week, have been found to develop supraspinatus tendinopathy with an associated tendon thickening (Sein, 2010). With a damaged and thickened rotator cuff tendon filling the subacromial space, swimmers have an increased potential to develop impingement syndrome and suffer from related chronic shoulder pain. What is more, 90% of those study participants stated they spent more than 50% of their training using the freestyle stroke, and only 13% swimming using the butterfly stroke, 21% in backstroke and 13% in breaststroke (Sein, 2010). This illustrates that high volume of freestyle swimming, whether performed with normal or faulty biomechanics, will likely lead to shoulder pain in the competitive swimmer.

Additionally, swimmers often display altered physical characteristics which could predispose them to shoulder pain. Commonly tight pectoralis major muscles and thoracic kyphosis posture in swimmers can lead to adverse muscle imbalances which often create decreases in subacromial space (M. Pink, et al., 1991; M. M. Pink & Tibone, 2000).

Swimmers also frequently display limited shoulder internal rotation range of motion as well as shoulder external rotation hypermobility (Bak & Magnusson, 1997; Beach, et al., 1992). Stability of this joint is essential for proper joint mechanics and without it, the competitive swimmer may experience significant disability and probable shoulder pathology (McMaster, et al., 1998). The presence of any of these common physical characteristics found among the swimming athlete may create abnormal joint function and increased stress on the shoulder, resulting in shoulder pain (M. M. Pink & Tibone, 2000). Perhaps the inclusion of posture and shoulder range of motion measurements, clinical examination results, and increased details on training trends of the study participants, will enhance the current model regarding incidence of chronic shoulder pain in competitive swimmers.

During video evaluation, the swimming coach evaluators initially expressed difficulty differentiating between incorrect freestyle biomechanics based on the provided criteria and a freestyle stroke which they would consider poor performance technique. The Certified Athletic Trainer evaluator did not express this issue and scored errors based strictly on the criteria listed by the primary investigator. This discussion suggests that swimming coaches observe freestyle biomechanics mainly for performance purposes, and that a stroke cycle which may be deemed as the best stroke biomechanics for performance by a coach may not utilize the biomechanics which best protect the shoulder from overuse injury. The underwater phase of the freestyle stroke holds possibly the greatest discrepancy between what is mechanically efficient for the shoulder and which mechanics best enhance performance. While maintaining a "straight back" pull-through during freestyle is deemed safest for a swimmer's shoulder girdle, coaches recognize a pull-through with a down-sweep, in-sweep, and out-sweep to produce performance gains and increased swimming velocity (L.

C. Seifert, D. Mujika I., 2011). It is thought that utilizing a curvilinear motion during the freestyle pull-through best produces propulsion by constantly pushing water and gaining additional resistance, rather than pushing water which has already been accelerated by a straight back stroke path (Colwin, 2002). Whether this is a deliberate attempt to scull or a phenomenon caused by the swimmer's natural rotation in the water, this not only closely mimics the faulty S-shaped pull-through pattern which can lead to increased time spent in the impingement position, but it also forces the shoulder to maintain increased muscle recruitment and higher loads over a longer period of time (Colwin, 2002; Johnson, et al., 2003; L. C. Seifert, D. Mujika I., 2011; Wilk, et al., 2009; Yanai & Hay, 2000).

The lack of significant results also indicates that the movement error scoring system used in this study was not predictive of shoulder pain. The definitions of biomechanical errors could potentially be altered to provide evaluators with clearer criteria and instructions during the film evaluation process. The primary investigator could better delineate timing within the stroke cycle of where certain errors may be occurring. It may also be helpful to provide evaluators with guiding marks on the film, such as lines through the midline of the subject's body. This could lead to less ambiguity with grading, as the presence of some errors might be more objectively defined through an improved evaluation process.

The Penn Shoulder Score was used to evaluate shoulder pain among subjects. It was scored out of 100 total points with 30 possible points representing the subject's pain, 10 possible points regarding shoulder satisfaction, and 60 possible points representative of their shoulder function. A lower total score was indicative of greater shoulder pain and disability. The Penn Shoulder Score's use of three separate subscales allowed swimmers to rate their shoulder function and shoulder satisfaction, both of which are important and commonly reported to swimming coaches and swimming Athletic Trainers when shoulder pain is present. This survey also forms a total score to encompass magnitude of shoulder pain at rest, during activities of daily living, and during strenuous activities, providing a thorough history to summarize each subject's status. However, the Disabilities of the Arm, Shoulder and Hand (DASH) Outcome Measure may be a more informative shoulder pain scale for this study when used with an appropriate sample size. The DASH is a self-report questionnaire which examines function and symptoms in patients who are experiencing musculoskeletal disorders of the upper limb. There is a sport module within this questionnaire, which identifies difficulties athletes may experience while performing their specific athletic activity. The DASH questionnaire has also been evaluated among competitive Division I and II collegiate athletes in which overhead athletes were found to score significantly lower on the total DASH score and the DASH sports module, in comparison to athletes competing in non-overhead sports (Hsu JE, 2010). Additionally, this measurement has been deemed valid when used as either a one-time measure or to determine change over time, which may be beneficial if this study were to be modified (Beaton D, 2001). The DASH may provide more appropriate information to the researcher studying a competitive swimming population.

Other upper extremity outcome measures could also be useful to evaluate shoulder pain in elite competitive swimmers. The American Shoulder and Elbow Surgeons self-report form encompasses self-assessment questions that examine pain, instability, and medication use and takes under 5 minutes to administer (Stiller, 2005). Pain, function, and select range-of-motion and manual muscle test scores are involved in this outcome measure, which has been demonstrated to be reliable, valid, and responsive (Michener LA, 2002). Use of this assessment form would provide essential information on shoulder pain in the overhead swimming athlete as well as evidence on physical characteristics as contributing factors to pain scores.

LIMITATIONS

There were several limitations to this study that warrant acknowledgement. Due to inoperative filming equipment half way through the study, 31 subjects were filmed, which is fewer than the originally anticipated 60 subjects. The anticipated 60 subjects and 120 independent shoulders would have yielded a projected power of 0.80. Collecting data on only 31 subjects, and therefore 62 independent shoulders, resulted in a power of just 0.27. The smaller sample size decreased the power of the study significantly and potentially contributed to results which were not statistically significant. The post-hoc power estimation indicates that there is only a 27% chance that a statistically significant finding could be identified if it existed. Using a greater number of subjects may have resulted in more significant correlations between faulty freestyle swimming biomechanics and shoulder pain, as well as increased the power of the study.

In addition to the small sample size, the inclusion criteria for the study may have contributed to non-significant findings. We excluded individuals who were unable to complete practices fully due to pain, injury, or illness at the time of the testing session. This exclusion may have decreased the variability in the Penn shoulder scores. **(Figure 9)** Including subjects who are injured, barring swimmers who are not medically cleared to participate in practice, may provide a greater distribution of Penn shoulder scores and lead to more significant relationships between stroke technique errors and shoulder pain.

Lastly, some freestyle biomechanics were more difficult to evaluate on film than others. This was often due to high amounts of splashing by the subject while swimming. Also, evaluators felt that certain errors were more objectively identifiable than others, sometimes increasing the difficulty of classifying the presence of specific errors. Evaluators conveyed that the errors of thumb-first hand entry and incorrect hand entry position were presented very clearly, both in criteria details and on film. They expressed moderate difficulty with evaluation of S-shaped pull-through, dropped elbow during recovery, and eyes-forward head carrying angle most often due to camera angle or splashing of water. Perhaps to ensure sagittal plane film is captured from a view which is parallel to the camera, subjects should be asked to swim multiple trials of freestyle. This would provide the primary investigator with additional stroke cycles to choose from when clipping the videos, and a greater likelihood of selecting film that best portrays the biomechanics in question.

The evaluators also suggested the use of a sliding scale evaluation technique of the biomechanical errors, instead of a "yes" or "no" categorization. The criteria asked evaluators to label swimmers as displaying an error if the incorrect element occurred anywhere within the stroke pattern. However, evaluators stated that it seemed odd to label both excessive and slight errors during a stroke phase with the same grade. This confusion may have led to grading difficulty and could be at fault for the poor agreement statistics between evaluators.

FUTURE RESEARCH

Future research is needed to better examine the relationship between freestyle biomechanical errors and shoulder pain. A study which examines the relationship of factors outside of biomechanics may be of benefit to identifying contributors to shoulder pain in elite competitive swimmers. Evaluation of training regimens, physical characteristics, and swimming performance among a group of competitive swimmers could provide useful injury prevention information for those individuals who are working with this population.

If this study were to be recreated, observation of the specific biomechanics would potentially need to be modified. Other research on freestyle biomechanics evaluation has further divided the phases of the stroke in the sagittal plane. Perhaps separating the underwater freestyle pull-through into a pull and push phase would have allowed coaches to more easily define the timing and presence of a specific error (Colwin, 2002). Providing options for evaluators to label errors as excessive or moderate may also encourage less indecision while grading the errors. It may be beneficial to provide the evaluators with additional film evaluation practice, as well as show each specific error on video, rather than just through still photos.

It is also suggested that freestyle biomechanics be filmed and pain scores be reported multiple times during the season if a similar study is recreated. This will better track possible alterations in technique and potential increases in shoulder pain, when volume and intensity change throughout the season. It is also recommended that all swimmers, regardless of their practice modifications in the swimming pool due to shoulder pain, be participants in the study. Film for this study was also recorded on a day in which the swimmers did not participate in an organized team practice. These data collection elements could have contributed to minimal reports of shoulder pain, and thus, a poor relationship between stroke errors and overall shoulder pain scores. Reworking these components of the study could produce results which better reflect the true relationship between these variables.

CONCLUSION

The results of this study did not find freestyle biomechanical errors to be a significant predictor of shoulder pain in elite competitive swimmers. The lack of significant findings can be attributed to very low power in the study, as well as the need to include other biomechanical, participation, and physical characteristic factors to evaluate this relationship. Conducting further research with an ambition to help develop additional shoulder injury prevention techniques in the competitive swimming athlete will better assess the true relationship between these variables.

SUMMARY OF RESEARCH QUESTIONS

Question	Description	Data Source	Comparison	Method
1	Does the total number of biomechanical freestyle stroke errors predict shoulder pain in elite competitive swimmers?	The total number of freestyle biomechanical errors per shoulder	The Penn Shoulder Score and total error score	Logistical regression
2	Is there a relationship between shoulder pain scores and the presence of a specific biomechanical freestyle stroke error in elite competitive swimmers?	The specific freestyle biomechanical errors found per shoulder	The Penn Shoulder Score and presence of specific biomechanical errors	Step-wise multiple logistical regression

FIGURES

Figure 1A: Correct hand entry angle: fingers first entry

Figure 1B: Incorrect hand entry angle: thumb first entry

Figure 2A: Correct hand entry position: medial to head and lateral to shoulder

Figure 2B: Incorrect hand entry position: hand enters too medially (i) or too laterally (ii)

Figure 3A: Correct pull-through pattern: Straight back pull-through

Figure 3B: Incorrect pull-through pattern: excessive horizontal adduction (S-shaped pattern)

Figure 4A: Correct elbow position during pull-through: Elbow kept higher than wrist, pointing laterally

Figure 4B: Incorrect elbow position during pull-through: dropped elbow

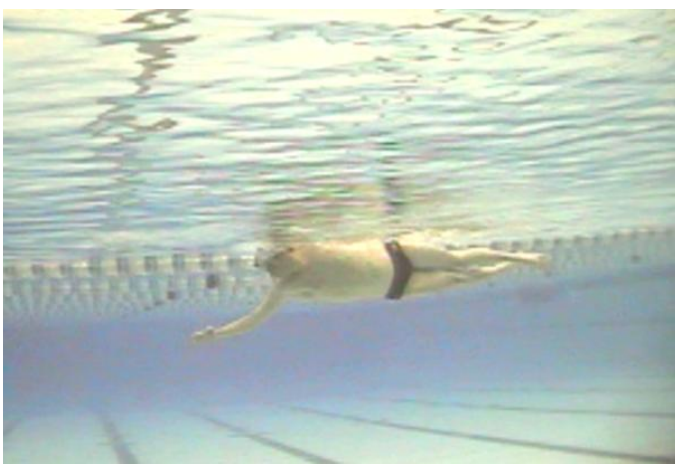


Figure 5A: Correct elbow position during recovery: elbow kept higher than wrist

Figure 5B: Incorrect elbow position during recovery: dropped elbow

Figure 6A: Correct body roll angle: body roll of at least 45° occurring along the longitudinal axis of the body

Figure 6B: Incorrect body roll angle: excessive body roll (i) or lack of body roll (ii)

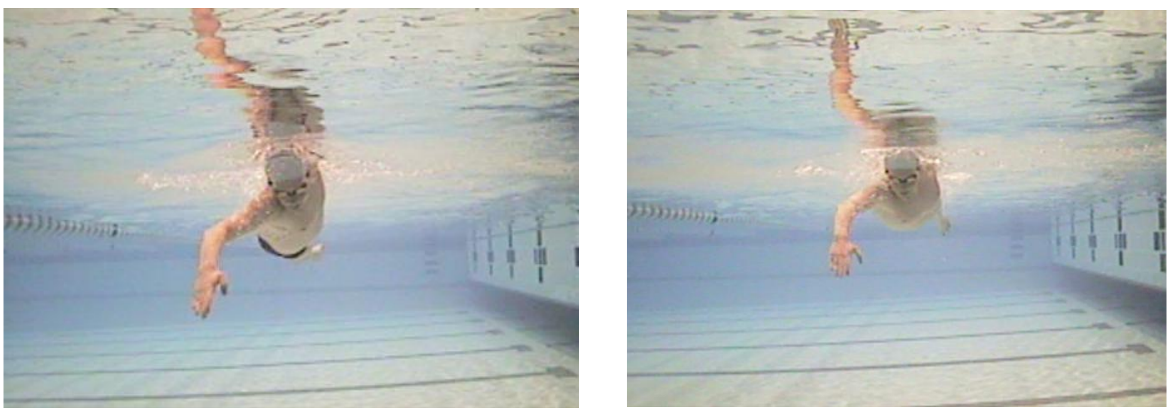


Figure 7A: Correct head carrying angle: neutral head position

Figure 7B: Incorrect head carrying angle: eyes-forward head position

Figure 8: Camera set-up for filming of biomechanics

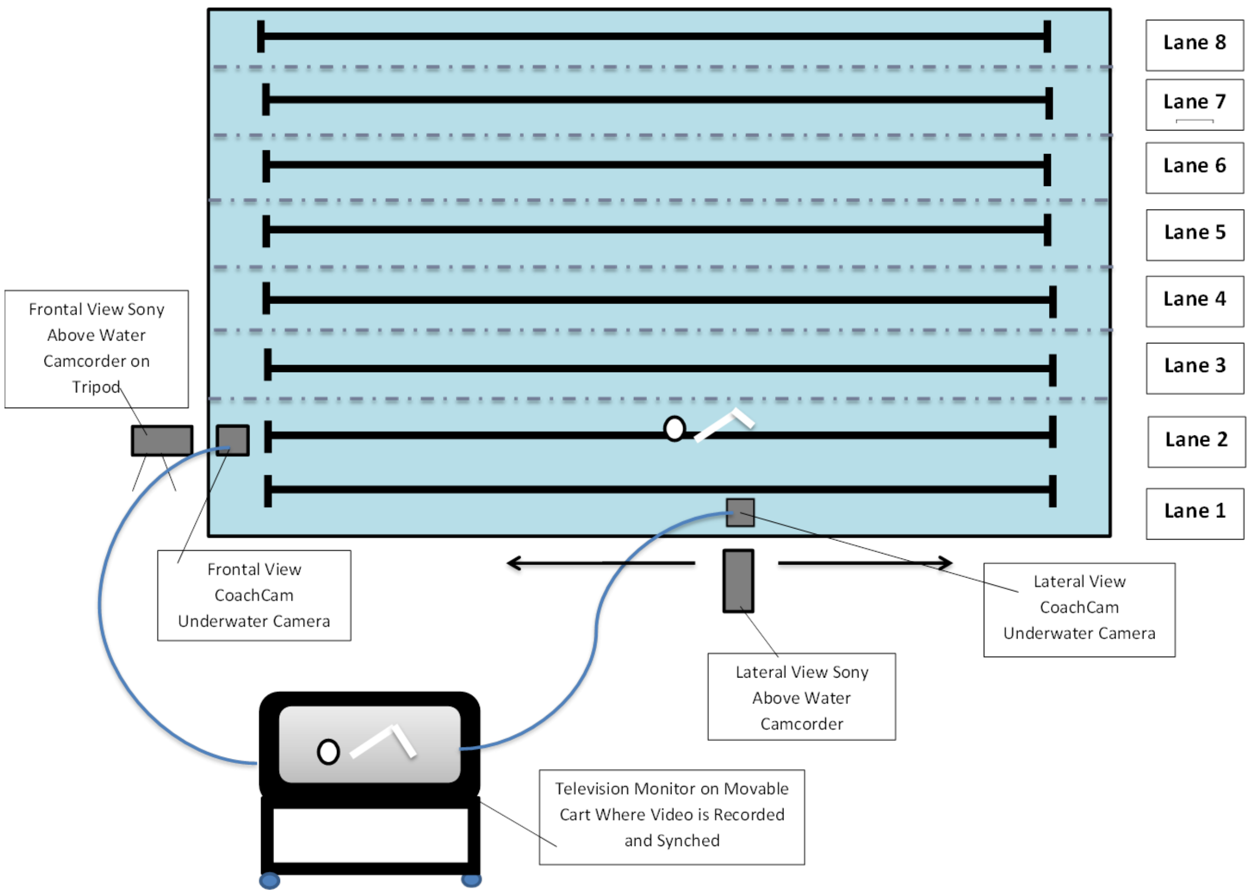


Figure 9: Penn Shoulder Score Distribution

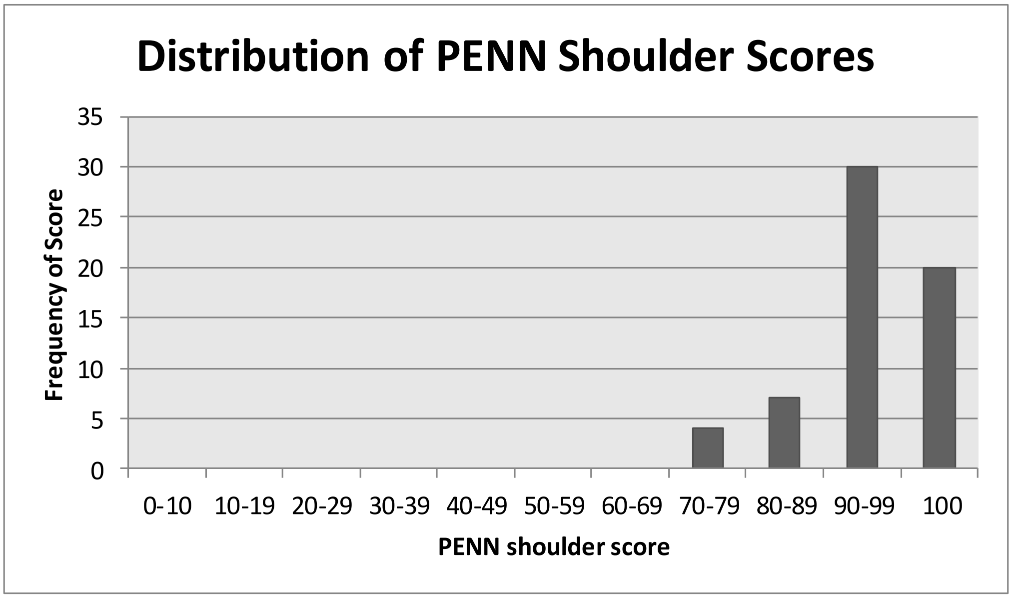


Figure 10: Distribution of Specific Biomechanical Errors

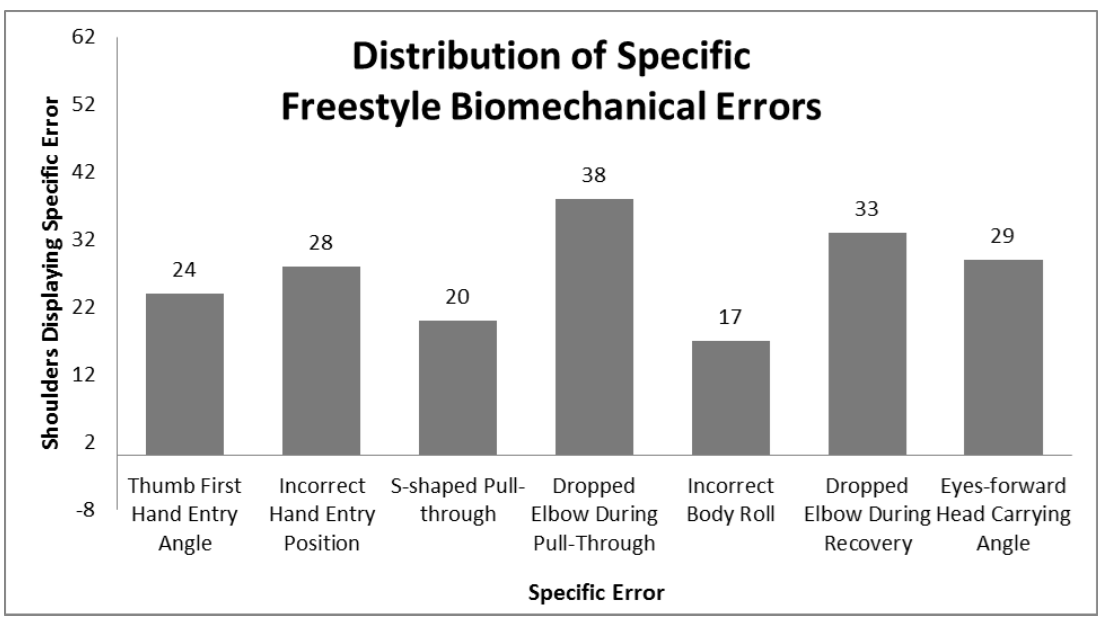
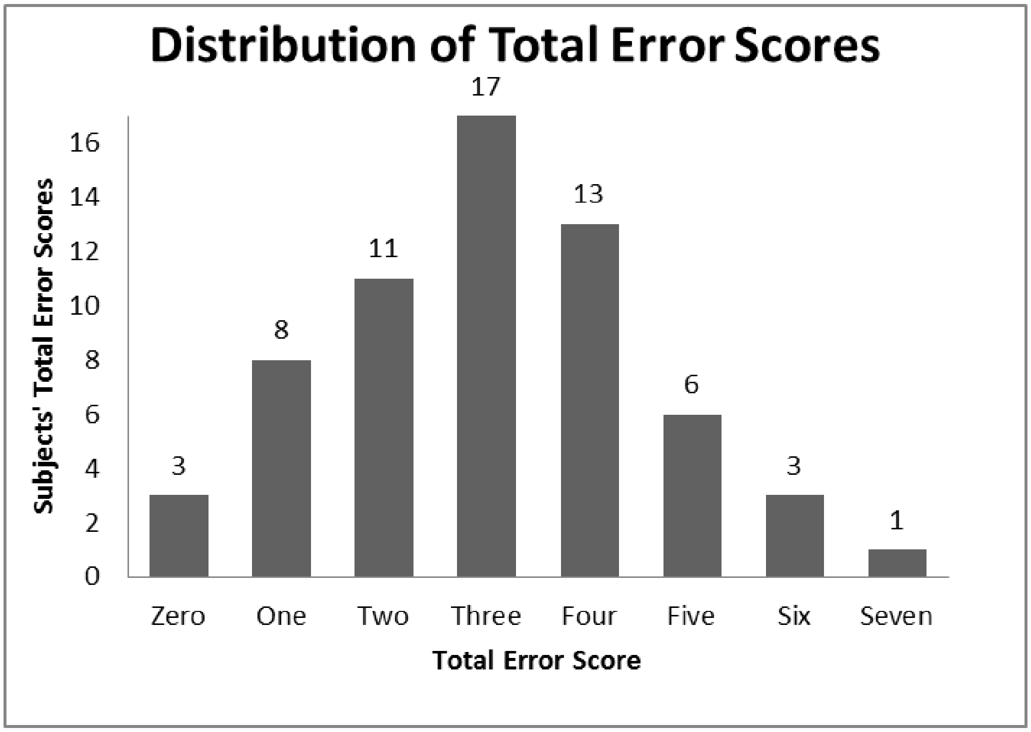


Figure 11: Distribution of Total Error Scores



TABLES

TABLE 1: FREESTYLE BIOMECHANICAL PARAMETERS

Stroke Phase	Correct Freestyle Biomechanics	Incorrect Freestyle Biomechanics	Relevance of Incorrect Biomechanics to Shoulder Pain
Hand Entry	Hand enters water forward and lateral to the head, medial to the shoulder. (M. Pink, et al., 1991)	Hand enters further away from or crosses the midline of the long axis of the body. (Johnson, et al., 2003; Scovazzo, et al., 1991; Wilk, et al., 2009)	Increases impingement to the anterior shoulder. (Johnson, et al., 2003) Mimics Neer impingement testing position (Wilk, et al., 2009)
	Little finger or fingers first hand entry. (Johnson, et al., 2003)	Thumb first hand entry. (Johnson, et al., 2003)	Stresses the biceps attachment to the anterior labrum. (Johnson, et al., 2003)
Pull-Through	Elbow kept higher than hand and points laterally throughout pull. (Colwin, 2002)	Dropped elbow during pull-through. (Yanai & Hay, 2000)	Increases external rotation, placing muscles of propulsion at mechanical disadvantage. (Richardson, et al., 1980)
	Swimmer should use a straight back pull-through. (Colwin, 2002)	S-shaped pull through or excessive horizontal adduction past body midline during pulling. (Johnson, et al., 2003)	Increases time spent in the impingement position. (Johnson, et al., 2003) Mimics Hawkins Kennedy impingement testing position of horizontal adduction, flexion, and internal rotation.
Recovery	Elbow kept higher than the wrist throughout the recovery phase (Johnson, et al., 2003; Yanai & Hay, 2000)	Dropped elbow during recovery phase (Wilk, et al., 2009)	Leads to an improper entry position with the elbow entering the water before the hand. The water will cause an upward force on the dropped humerus, leading to its superior translation and subacromial impingement in the shoulder. (Wilk, et al., 2009)
	Body roll of ~45° along the longitudinal axis of the body (Colwin, 2002; Johnson, et al., 2003)	Body roll that is greater or less than 45° (Johnson, et al., 2003)	Excessive roll can lead to crossover entry position, during the pull phase, or during both phases. A lack of roll during recovery can increase mechanical stress on the shoulder and lead to improper hand entry position. (Johnson, et al., 2003)
All Phases	Head in neutral position. Imagine line through center of head and extending length of the spine. (Johnson, et al., 2003)	Head carriage is in eyes forward position. (Johnson, et al., 2003)	Eyes forward head position increase impingement by impending normal scapulothoracic motion. (Johnson, et al., 2003)

TABLE 2: SUBJECT DEMOGRAPHICS

Subject Demographics

Number of Subjects (n)	31
Male/Female	16/15
Age (years)	20 ± 1.41
Height (cm)	179.1716 ± 9.65
Mass (kg)	75.43 ±8.64
Years of Competitive Swimming Experience	11.3 ± 3.49

TABLE 3: EVALUATOR KAPPA AGREEMENTS

Biomechanical Error	**Kappa Agreements**
Thumb-first hand entry (Johnson, et al., 2003)	0.414
Hand crosses the long axis midline of the body or is placed lateral to shoulder at entry (Johnson, et al., 2003; Scovazzo, et al., 1991)	0.323
S-shaped pull-through or excessive horizontal adduction during pulling (Johnson, et al., 2003; Wilk, et al., 2009; Yanai & Hay, 2000)	0.687
Dropped elbow during pull-through phase (Richardson, et al., 1980)	0.293*
Dropped elbow during recovery phase (Richardson, et al., 1980; Wilk, et al., 2009)	0.806
Body roll that is greater or less than the 35-45° (Johnson, et al., 2003)	0.012*
Head carriage is in eyes forward position. (Johnson, et al., 2003)	0.317

TABLE 4: CONTRIBUTION OF SPECIFIC ERRORS TO SHOULDER PAIN

Biomechanical Error	Beta Coefficient, Significance
Thumb-first hand entry (Johnson, et al., 2003)	$\beta = -0.076$, $p = 0.602$
Hand crosses the long axis midline of the body or is placed lateral to shoulder at entry (Johnson, et al., 2003; Scovazzo, et al., 1991)	$\beta = -0.150$, $p = 0.349$
S-shaped pull-through or excessive horizontal adduction during pulling (Johnson, et al., 2003; Wilk, et al., 2009; Yanai & Hay, 2000)	$\beta = 0.205$, $p = 0.145$
Dropped elbow during recovery phase (Richardson, et al., 1980; Wilk, et al., 2009)	$\beta = 0.234$, $p = 0.136$
Head carriage is in eyes forward position. (Johnson, et al., 2003)	$\beta = -0.122$, $p = 0.389$

TABLE 5: RELIABILITY STATISTICS

Biomechanical Error	Kappa Agreements Between Sessions
Thumb-first hand entry (Johnson, et al., 2003)	0.886
Hand crosses the long axis midline of the body or is placed lateral to shoulder at entry (Johnson, et al., 2003; Scovazzo, et al., 1991)	1.000
S-shaped pull-through or excessive horizontal adduction during pulling (Johnson, et al., 2003; Wilk, et al., 2009; Yanai & Hay, 2000)	0.900
Dropped elbow during pull-through phase (Richardson, et al., 1980)	1.000
Dropped elbow during recovery phase (Richardson, et al., 1980; Wilk, et al., 2009)	0.615
Body roll that is greater or less than the 35-45° (Johnson, et al., 2003)	0.688
Head carriage is in eyes forward position. (Johnson, et al., 2003)	0.700

APPENDICES

APPENDIX 1: PENN SHOULDER SCORE

The Penn Shoulder Score, Part 1: Pain and Satisfaction Subscales

Please circle the number closest to your level of pain or satisfaction	Office Use Only
Pain at rest with your arm by your side: 0 1 2 3 4 5 6 7 8 9 10 No pain ... Worst pain possible	_______ (10 – # circled)
Pain with normal activities (eating, dressing, bathing): 0 1 2 3 4 5 6 7 8 9 10 No pain ... Worst pain possible	_______ (10 – # circled) (Score 0 if not applicable)
Pain with strenuous activities (reaching, lifting, pushing, pulling, throwing): 0 1 2 3 4 5 6 7 8 9 10 No pain ... Worst pain possible	_______ (10 – # circled) (Score 0 if not applicable)
Pain score:	=____/30
How satisfied are you with the current level of function of your shoulder? 0 1 2 3 4 5 6 7 8 9 10 No pain ... Worst pain possible	____/10 (# circled)

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The Penn Shoulder Score: Function Subscale

Please circle the number that best describes the level of difficulty you might have performing each activity	No difficulty	Some difficulty	Much difficulty	Can't do at all	Did not do before injury
1. Reach the small of your back to tuck in your shirt with your hand	3	2	1	0	X
2. Wash the middle of your back/hook bra	3	2	1	0	X
3. Perform necessary toileting activities	3	2	1	0	X
4. Wash the back of opposite shoulder	3	2	1	0	X
5. Comb hair	3	2	1	0	X
6. Place hand behind head with elbow held straight out to the side	3	2	1	0	X
7. Dress self (including put on coat and pull shirt off overhead	3	2	1	0	X
8. Sleep on affected side	3	2	1	0	X
9. Open a door with affected arm	3	2	1	0	X
10. Carry a bag of groceries with affected arm	3	2	1	0	X
11. Carry a briefcase/small suitcase with affected arm	3	2	1	0	X
12. Place a soup can (1-2 lb) on a shelf at shoulder level without bending elbow	3	2	1	0	X
13. Place a one gallon container (8-10 lb) on a shelf at shoulder level without bending elbow	3	2	1	0	X
14. Reach a shelf above your head without bending your elbow	3	2	1	0	X
15. Place a soup can (1-2 lb) on a shelf overhead without bending your elbow	3	2	1	0	X
16. Place a one gallon container (8-10 lb) on a shelf overhead without bending your elbow	3	2	1	0	X
17. Perform usual sport/hobby	3	2	1	0	X
18. Perform household chores (cleaning, laundry, cooking)	3	2	1	0	X
19. Throw overhand/swim/overhead racquet sports (circle all that apply to you)	3	2	1	0	X
20. Work full-time at your regular job	3	2	1	0	X

SCORING
Total of columns = ____ (a)
Number of Xs × 3 =____(b), 60 – ____(b) = ____ (c) (if no Xs are circled, function score = total of columns)
Function Score = ____(a) ÷ ____(c) = ____ × 60 ____/60

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APPENDIX 2: BIOMECHANICS EVALUATION FORM

Subject	Error	Does the **right** arm display this error?		Does the **left** arm display this error?	
		Yes	No	Yes	No
1	Thumb first hand entry				
	Improper hand entry position				
	S-shaped pull-through/ excessive horizontal adduction				
	Dropped elbow during pull-through				
	Excessive or lack of body roll during recovery phase				
	Dropped elbow during recovery phase				
	Eyes forward head position				

APPENDIX 3: MANUSCRIPT

RELATIONSHIP BETWEEN FREESTYLE BIOMECHANICAL ERRORS AND SHOULER PAIN IN ELITE COMPETITIVE SWIMMERS

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INTRODUCTION

Swimming the freestyle stroke places significant stress on the shoulder. Continual repetition and intense demand are consistently placed on the shoulder causing it to be the most commonly injured joint in swimming athletes (Stocker, et al., 1995). "Swimmer's shoulder" is a general term frequently used to describe shoulder pain or injury experienced by a competitive swimmer (McMaster, et al., 1998). A major cause of these shoulder problems experienced by freestyle swimmers is thought to be impingement of subacromial structures in the shoulder during their stroke (Yanai, et al., 2000).

On average, swimmers at the collegiate level train between 40,000 and 50,000 yards per week and an elite swimmer may log up to 20,000 yards in one day (McMaster & Troup, 1993; Stocker, et al., 1995). In order to complete this amount of yardage during practice time, 80 percent of practice is completed in freestyle, regardless of stroke specialty. This allows the swimmers to complete the necessary yardage during practice time, but also places tremendous stress on the shoulder. It has been estimated that competitive swimmers will average about 18,000 shoulder revolutions per week mostly from the freestyle training (Beach, et al., 1992; M. Pink, et al., 1991).

Current research on proper swimming biomechanics is limited, making it difficult for any coach, swimmer, or investigator to agree on the correct freestyle stroke technique that both improves performance and decreases the risk of shoulder injury. While most studies have focused on performance advancement, some studies have identified errors in freestyle biomechanics that may place the swimmer in vulnerable positions for injury (Heinlein & Cosgarea, 2010; Johnson, et al., 2003; Richardson, et al., 1980; Yanai & Hay, 2000; Yanai, et al., 2000). Incorrect freestyle stroke biomechanics have been suggested as a possible risk factor for shoulder pain and pathology, but this has not been clearly observed in biomechanical or clinical studies (Johnson, et al., 2003; Yanai & Hay, 2000; Yanai, et al., 2000). While it has been suggested that faulty freestyle stroke mechanics may precede shoulder pain, there is still an unclear correlation between the two variables within swimming literature. Therefore, the purpose of this study is to examine the relationship between freestyle stroke movement errors and shoulder pain in elite competitive swimmers.

Materials and Methods

Thirty-one local club swimmers were asked to participate for this study. All subjects were competitive swimmers who were between 18 and 24 years old (age = 20 years ± 1.41, height = 179.17 cm ± 9.65, mass = 75.43 kg. ± 8.64). On average, participants swam competitively for 11.3 ± 3.49 years. Subjects were included in the study if they were regularly training at least 5 times per week for 1-2 hours each practice session, had at least 5 years competitive swimming experience, and were completing practice with no restrictions at the time of the video analysis. Subjects were excluded from this study if they were unable to complete practices fully due to pain, injury, or illness at the time of the testing session. All participants read and signed a consent form approved by the university's Institutional Review Board.

Video analysis of freestyle stroke patterns, Penn Shoulder Pain Scores, and movement error evaluation were collected on both shoulders of each swimmer. Thus, data were collected on sixty-two independent shoulders. All subjects completed the Penn Shoulder Score self-reporting questionnaire immediately prior to their participation in the study trials.

Video analysis was performed over 2 trials while swimming freestyle to capture both the right and left sides of the athlete. All trials were performed in a 25-yard indoor swimming pool where the team normally trains. Each swimmer was instructed to swim freestyle for 25 yards (one length of the swimming pool) at a pace 50-75 percent of their maximum race speeds, using their natural stroke technique. This was completed twice, resulting in a total of 50 yards swum by each subject.

An underwater camera was secured onto the telescopic pole that was held stationary by the operator who was standing on the pool deck. A Sony HDR-XR150 handheld camcorder was positioned on a stationary tripod set at the appropriate height and distance to capture the necessary filming area. The camera set up is illustrated in **Figure 8**. Both underwater cameras were connected to their own monitoring screen to record the frontal and lateral for later analysis using Dartfish® ProSuite (Dartfish Ltd.) video analysis software . The above water video data was also uploaded to a computer for analysis using Dartfish®.

Following all filming of trials, the primary investigator selected a stroke cycle for grading and clipped the video. A stroke cycle was considered for analysis if the hand entry, pull-through, and recovery phases were clearly visible in the combined underwater and land views of each camera when viewed in Dartfish® following filming. The primary investigator reviewed all camera angles. One complete stroke cycle was selected for each swimmer and each trial from a combination of each of the six camera views. Yanai and Hay (Yanai & Hay, 2000) described parameters for which a stroke cycle can be selected during video analysis. These parameters included 1) the cycle must be completely within the camera view, 2) the periscopes and underwater cameras must have captured the subject sufficiently well so that his/her body was positioned at the center of each field throughout filming, and 3) the image size of the subject projected on the monitor must be large enough to be viewed in the Dartfish® software. The first full stroke cycle to enter the camera view and meet the previous criteria was selected for evaluation. The primary investigator ensured the same stroke cycle was clipped using video synchronization of the underwater cameras via the Dartfish® software and visual guidance from the 15 yard and 5 yard lane rope markers on the above water camera film. Pilot testing of the filming protocol occurred prior to the study.

Two experienced swimming coaches and one Certified Athletic Trainer who had 5 and 7 years of experience working with the collegiate-level swimming team and had no knowledge of the swimmers' shoulder injury histories or freestyle strokes were asked to observe and evaluate the selected video clips of each subject's freestyle biomechanics. All 3 evaluators reported to the Koury Natatorium conference room at the University of North Carolina Chapel Hill for grading of video analysis on a selected date following filming and clipping of all subjects' freestyle stroke cycles. All examiners underwent standardized training through the use of still photographs of the 7 biomechanical parameters and sample video examples of correct and incorrect freestyle biomechanics prior to the evaluator reviewing the selected freestyle stroke cycles of each swimmer. This served as a practice evaluation before the actual test trial videos were presented to the group, which was completed on the same day. The following parameters were applied to the right and left arm of each swimmer:

(e) Hand Entry

(i) Correct biomechanics **(Figure 1 A):** Fingers-first or little finger-first entry(Johnson, et al., 2003; M. Pink, et al., 1991)

(ii) Incorrect biomechanics **(Figure 1B):** Thumb-first entry(Johnson, et al., 2003)

(iii) Correct biomechanics **(Figure 2A):** Hand enters lateral to head and medial to shoulder(M. Pink, et al., 1991)

(iv) Incorrect biomechanics **(Figure 2B):** Hand crosses the long axis midline of the body or is placed lateral to shoulder at entry (Johnson, et al., 2003; Scovazzo, et al., 1991)

(f) Pull-through

(i) Correct biomechanics **(Figure 3A):** Straight back pull-through(Colwin, 2002; Johnson, et al., 2003)

(ii) Incorrect biomechanics **(Figure 3B):** S-shaped pull-through or excessive horizontal adduction during pulling(Johnson, et al., 2003; Wilk, et al., 2009; Yanai & Hay, 2000)

(iii) Correct biomechanics **(Figure 4A):** Elbow kept higher than wrist, pointing laterally, reaching maximum bend at half-way through pull(Colwin, 2002)

(iv) Incorrect biomechanics **(Figure 4B):** Dropped elbow (Richardson, et al., 1980)

(g) Recovery

(i) Correct biomechanics **(Figure 5A):** Elbow kept higher than wrist throughout the phase(Colwin, 2002; Wilk, et al., 2009)

(ii) Incorrect biomechanics **(Figure 5B):** Dropped elbow(Richardson, et al., 1980; Wilk, et al., 2009)

(iii) Correct biomechanics **(Figure 6A):** Body roll of 35-45° occurs along the longitudinal axis of the body (Colwin, 2002; Johnson, et al., 2003)

(iv) Incorrect biomechanics **(Figure 6B):** Excessive or lack of body roll angle (Johnson, et al., 2003)

(h) Not phase-specific

(i) Correct biomechanics **(Figure 7A):** Head in neutral position (Johnson, et al., 2003)

(ii) Incorrect biomechanics **(Figure 7B):** Head carriage is in eyes forward position (Johnson, et al., 2003)

After all questions were answered and the primary investigator determined that the evaluators understood the parameters, grading of the videos began. Each evaluator was provided with a form to evaluate the biomechanical errors for each subject. Observers were able to ask the investigator to replay a phase or parameter view but they were not permitted to ask to return to a previous swimmer's trial once grades had been finalized for that participant. Observers were blinded to the other evaluators' grades during the process. The right and left arms of each subject were evaluated independently, thus a total error score was provided for the left and right side of each swimmer. Each of the 7 parameters were graded as a *yes* or *no* by each evaluator after reviewing the selected stroke cycle from all camera angles. The primary investigator used a majority rules method to decide upon a final grade for the presence of each biomechanical error. The final total error score for each subject had a potential range of 0/7 errors to 7/7 errors.

Reliability of the evaluation criteria for specific biomechanical errors and total error scores was examined. The primary investigator graded a sample of 10 subjects' film on two separate occasions. The kappa values for each specific error were determined by examining the agreement between grades from both evaluation sessions. The reliability kappa statistics for each biomechanical error are as follows: thumb-first hand entry (kappa = 0.886), improper hand entry position (kappa = 1.000), S-shaped pull-through or excessive horizontal adduction during pulling (kappa = 0.900), dropped elbow during pull-through phase (kappa = 1.000), dropped elbow during recovery phase (kappa = 0.615), body roll that is greater or less than the 35-45° (kappa = 0.688), and head carriage is in eyes forward position (kappa = 0.700). The Spearman correlation coefficient was used to assess the relationship between total error scores from both evaluation sessions. There was a positive correlation between total error scores from both evaluation sessions (r = 0.934, n = 20, p = .000). Overall, this evidence supports strong intra-rater reliability among multiple grading sessions performed by a single evaluator.

Statistical Analyses

A logistic regression was performed to determine if the total error score (the number of freestyle biomechanical errors) predicted the pain score in elite competitive swimmers. A step-wise multiple logistic regression were performed to examine the specific biomechanical parameters that most significantly predict shoulder pain scores in elite competitive swimmers. An a priori alpha level of 0.05 was set. Statistical analyses were run using SPSS version 19.0 (SPSS Inc., Chicago, IL). Power analysis indicates that 60 subjects were needed, however data on only 31 subjects were able to be collected. While seven freestyle stroke biomechanical errors were originally examined in the evaluation process, kappa statistics were calculated to provide a measurement of reliability and precision between the evaluators' grades to determine which variables would be added into the regression equation. A kappa agreement (< 0.30) was found between evaluators' grades for the errors of excessive or lack of body roll (kappa = 0.012) and dropped elbow during the pull-through phase (kappa = 0.293) and therefore, these two errors were excluded from further statistical analyses because of their poor reliability.

While the intra-rater reliability determined by the primary investigator's multi-session evaluation grades was strong, these kappa agreements reveal low homogeneity among the three evaluators and poor inter-rater reliability. This information suggests the evaluation criteria may need refined or the raters may have needed to be trained differently prior to the final evaluation process.

Results

A multivariate linear regression was performed to determine if the total number of technique errors predicted PENN Shoulder Score. The results of the regression indicate that the total error score explained 0% of the variance in the PENN shoulder score (R^2 = 0.00, $F_{1,60}$ = 0.006, p = 0.936). The total number of biomechanical errors was not predictive of the PENN shoulder score.

Additionally, a multiple linear regression was used to evaluate if specific biomechanical errors could significantly predict PENN shoulder pain score in competitive swimmers. The results of the regression indicate that the specific biomechanical errors explain only 6.5% of the variance (R^2 = 0.065, $F_{5,56}$ = 0.782, p = 0.567). None of the specific biomechanical errors significantly predicted the PENN shoulder pain score. The measurement of contribution of each specific freestyle stroke error to shoulder pain is expressed through the following results: thumb-first hand entry angle (β = -0.076, p = 0.602), incorrect hand entry position (β = -0.150, p = 0.349), S-shaped pull-through pattern (β = 0.205, p = 0.145), dropped elbow during recovery (β = 0.234, p = 0.136), and eyes forward head carrying angle (β = -0.122, p = 0.389). This data is presented in **Table 1** and the distribution of shoulder pain score is illustrated in **Figure 9**.

The distribution of specific errors observed among the subjects was somewhat related to the kappa agreement statistics. While evaluators felt only 17 out of 62 shoulders displayed improper amounts of body roll during the stroke cycle, there was also a poor agreement of 0.012 among their grades. It is possible that the low number of subjects evaluated as displaying this error was related to the poor evaluation agreement, which may have stemmed from unclear definitions of biomechanics or unclear camera views. A distribution of the subjects displaying specific errors as well as a graph encompassing the distribution of total error scores can be found in **Figure 10** and **Figure 11**, respectively.

Discussion

While there were no statistically significant findings which indicated a relationship between shoulder pain scores and the presence of freestyle biomechanical errors, it is important to note that only 6.5% of the variance was explained by the specific biomechanical errors. This indicates that there may be other factors, aside from the biomechanics that have been theorized as risk factors for shoulder pain, which are influential in shoulder pain scores. Unilateral breathing in subjects without shoulder pain has been associated with a small magnitude of scapular tilt angle, increased shoulder impingement on the ipsilateral side, and therefore increased likelihood of shoulder pain development (Yanai & Hay, 2000). Our filming instructions eliminated a biomechanical factor which could have shown a possible relationship to shoulder pain. Also, flutter kicking rhythm typically alters arm coordination and would therefore be a potential biomechanical factor responsible for shoulder pain (Maglischo, 2003). Swimmers with a weak kick, regardless of the rhythm, would need to accelerate their stroke rate which will likely increase overall number of overhead strokes taken per length of the pool. Overall timing and synchronization of the arms and legs during the freestyle stroke may also be important to analyze when studying swimming biomechanics in relation to shoulder pain. Entering the recovery arm into the water too early or too late can force a swimmer to alter their pull-through stroke pattern by making their insweep shorter or wider, and potentially placing the shoulder in a vulnerable impingement position (Maglischo, 2003).

In addition to biomechanical errors during training, there may be other participation factors related to the development of shoulder pain. Coaches believe that successful performance in competitive swimming requires a combination of endurance and power, which is developed through these high loads of swimming. However, swimmers who undergo large amounts of training, specifically greater than 15 hours of swimming per week, have been found to develop supraspinatus tendinopathy with an associated tendon thickening (Sein, 2010). With a damaged and thickened rotator cuff tendon filling the subacromial space, swimmers have an increased potential to develop impingement syndrome and suffer from related chronic shoulder pain. This illustrates that high volume of freestyle swimming, whether performed with normal or faulty biomechanics, will likely lead to shoulder pain in the competitive swimmer.

Additionally, swimmers often display altered physical characteristics which could predispose them to shoulder pain and the presence of any altered characteristics found among these athletes may create abnormal joint function and increased stress on the shoulder, resulting in shoulder pain (M. M. Pink & Tibone, 2000). Perhaps the inclusion of posture and shoulder range of motion measurements, clinical examination results, and increased details on training trends of the study participants, will enhance the current model regarding incidence of chronic shoulder pain in competitive swimmers.

The lack of significant results also indicates that the movement error scoring system used in this study was not predictive of shoulder pain. The definitions of biomechanical errors could potentially be altered to provide evaluators with clearer criteria and instructions during the film evaluation process. The primary investigator could better delineate timing within the stroke cycle of where certain errors may be occurring. It may also be helpful to provide evaluators with guiding marks on the film, such as lines through the midline of the subject's body. This could lead to less ambiguity with grading, as the presence of some errors might be more objectively defined through an improved evaluation process.

Limitations

There were several limitations to this study that warrant acknowledgement. Due to inoperative filming equipment half way through the study, 31 subjects were filmed, which is fewer than the originally anticipated 60 subjects and resulted in a power of just 0.27. Also, during video evaluation, the swimming coach evaluators initially expressed difficulty differentiating between incorrect freestyle biomechanics based on the provided criteria and a freestyle stroke which they would consider poor performance technique. This discussion suggests that swimming coaches observe freestyle biomechanics mainly for performance purposes, and that a stroke cycle which may be deemed as the best stroke biomechanics for performance by a coach may not utilize the biomechanics which best protect the shoulder from overuse injury.

Future Research

More research is needed to better examine the relationship between freestyle biomechanical errors and shoulder pain. A study which examines the relationship of factors outside of biomechanics may be of benefit to identifying contributors to shoulder pain in elite competitive swimmers. Evaluation of training regimens, physical characteristics, and swimming performance among a group of competitive swimmers could provide useful injury prevention information for those individuals who are working with this population.

If this study were to be recreated, observation of the specific biomechanics would potentially need to be modified. It is also suggested that freestyle biomechanics be filmed and pain scores be reported multiple times during the season if a similar study is recreated. It is also recommended that all swimmers, regardless of their practice modifications in the swimming pool due to shoulder pain, be participants in the study. Reworking these components of the study could produce results which better reflect the true relationship between these variables.

Conclusion

The results of this study did not find freestyle biomechanical errors to be a significant predictor of shoulder pain in elite competitive swimmers. The lack of significant findings can be attributed to very low power in the study, as well as the need to include other biomechanical, participation, and physical characteristic factors to evaluate this relationship. Conducting further research with an ambition to help develop additional shoulder injury prevention techniques in the competitive swimming athlete will better assess the true relationship between these variables.

Word count: 2688

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FIGURE 1A: CORRECT HAND ENTRY ANGLE: FINGERS FIRST ENTRY

FIGURE 1B: INCORRECT HAND ENTRY ANGLE: THUMB FIRST ENTRY

FIGURE 2A: CORRECT HAND ENTRY POSITION: MEDIAL TO HEAD AND LATERAL TO SHOULDER

FIGURE 2B: INCORRECT HAND ENTRY POSITION: HAND ENTERS TOO MEDIALLY (I) OR TOO LATERALLY (II)

FIGURE 3A: CORRECT PULL-THROUGH PATTERN: STRAIGHT BACK PULL-THROUGH

FIGURE 3B: INCORRECT PULL-THROUGH PATTERN: EXCESSIVE HORIZONTAL ADDUCTION (S-SHAPED PATTERN)

FIGURE 4A: CORRECT ELBOW POSITION DURING PULL-THROUGH: ELBOW KEPT HIGHER THAN WRIST, POINTING LATERALLY

FIGURE 4B: INCORRECT ELBOW POSITION DURING PULL-THROUGH: DROPPED ELBOW

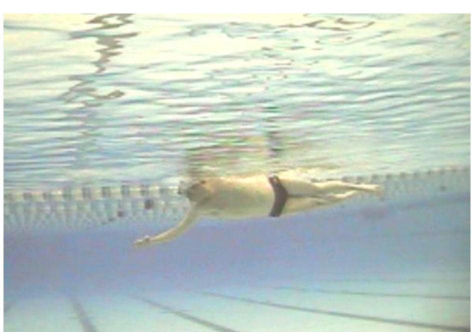


FIGURE 5A: CORRECT ELBOW POSITION DURING RECOVERY: ELBOW KEPT HIGHER THAN WRIST

FIGURE 5B: INCORRECT ELBOW POSITION DURING RECOVERY: DROPPED ELBOW

FIGURE 6A: CORRECT BODY ROLL ANGLE: BODY ROLL OF AT LEAST 45° OCCURRING ALONG THE LONGITUDINAL AXIS OF THE BODY

FIGURE 6B: INCORRECT BODY ROLL ANGLE: EXCESSIVE BODY ROLL (I) OR LACK OF BODY ROLL (II)

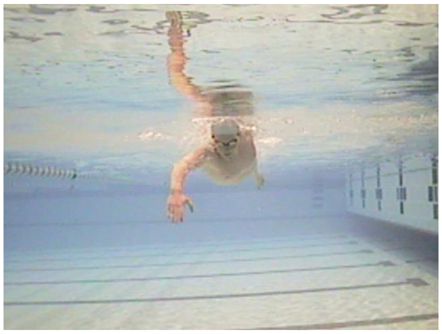


FIGURE 7A: CORRECT HEAD CARRYING ANGLE: NEUTRAL HEAD POSITION

FIGURE 7B: INCORRECT HEAD CARRYING ANGLE: EYES-FORWARD HEAD POSITION

FIGURE 8: CAMERA SET-UP FOR FILMING OF BIOMECHANICS

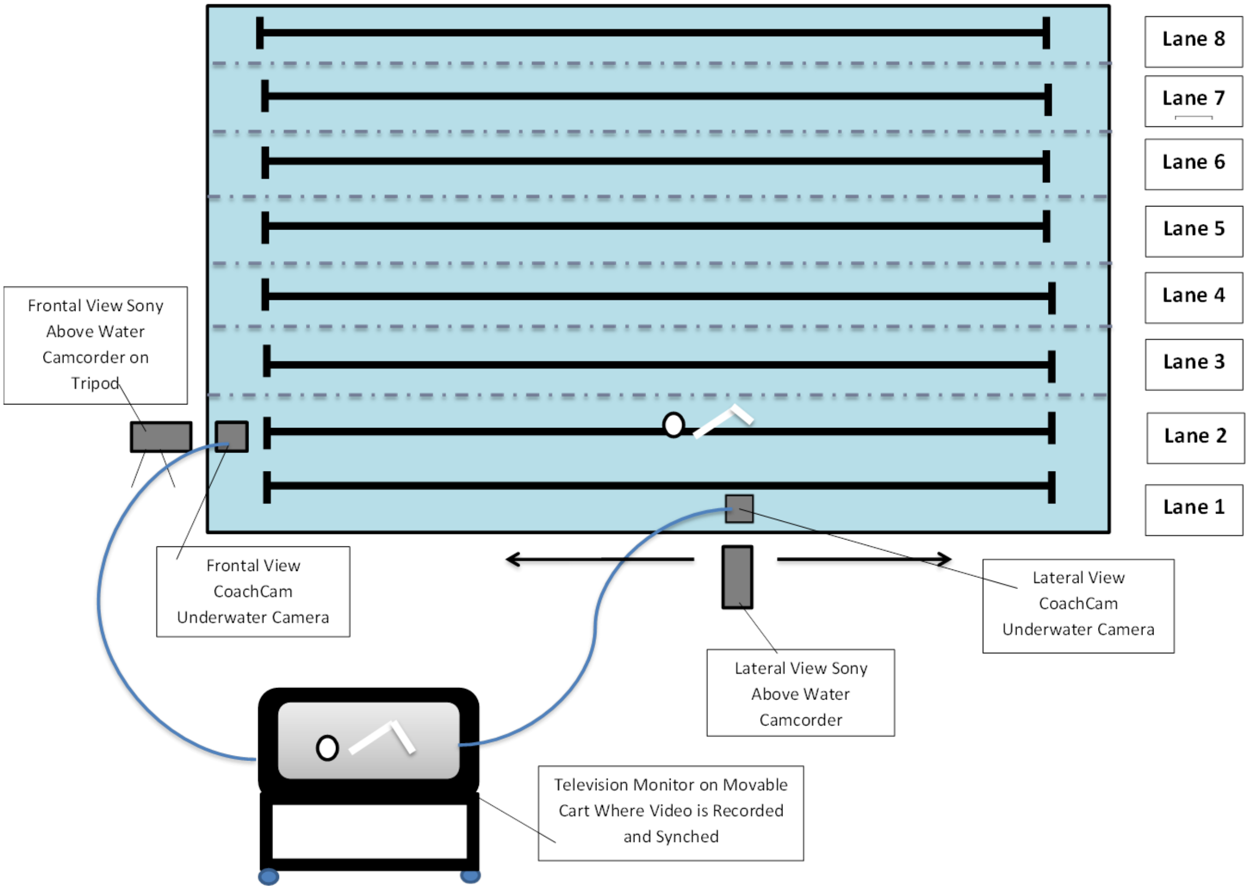


FIGURE 9: DISTRIBUTION OF PENN SHOULDER SCORES

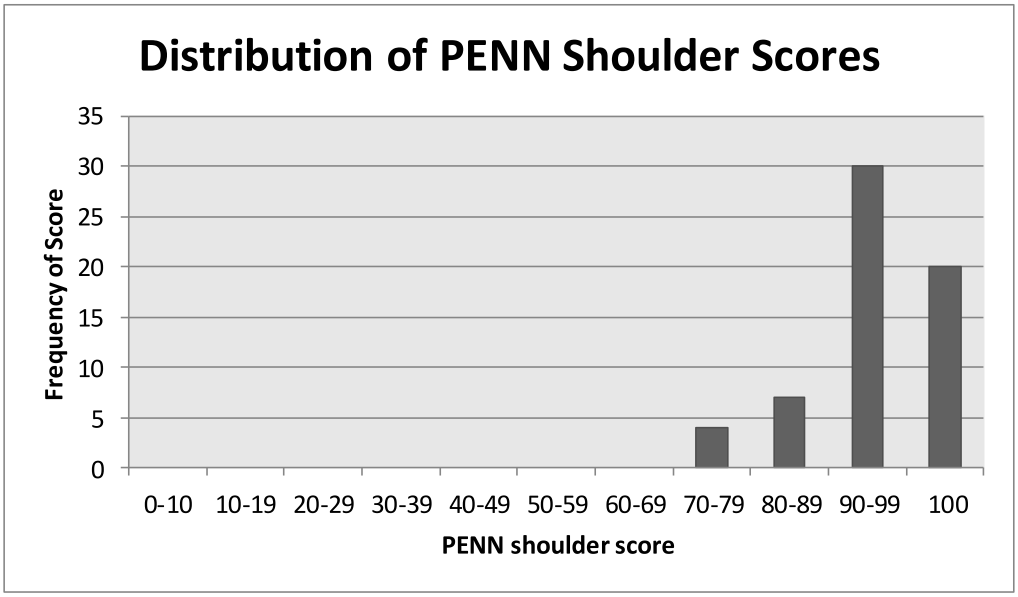


Figure 10: DISTRIBUTION OF SPECIFIC BIOMECHANICAL ERRORS

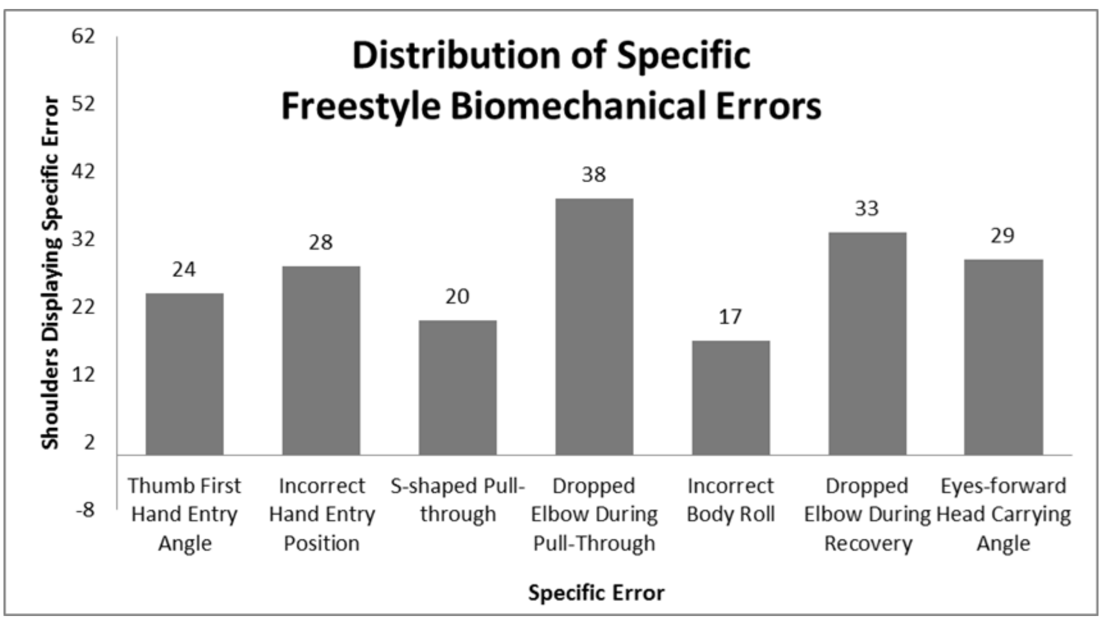
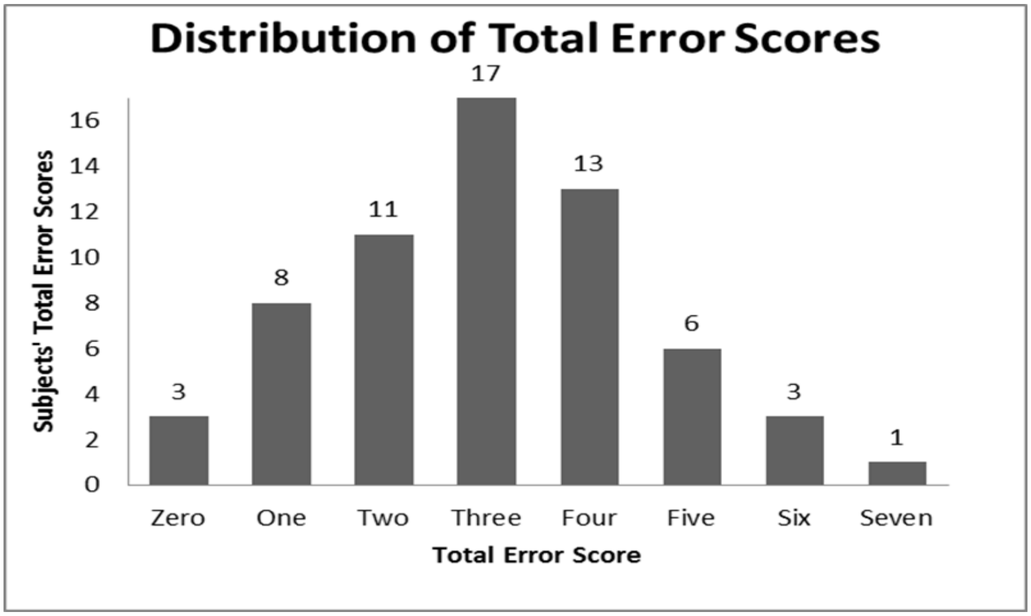


Figure 11: Distribution of Total Error Scores



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