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# The Relationship Between Lower Extremity Strength, Mobility, Movement Quality, and Pain in Collegiate Synchronized Swimmers

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# The Relationship between Lower Extremity Strength, Mobility, Movement Quality, and Pain in Collegiate Synchronized Swimmers

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In Partial Fulfillment

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By

Paula Borges Costa

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**The Relationship between Lower Extremity Strength, Mobility, Movement Quality, and Pain in Collegiate Synchronized Swimmers**

Human Performance
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Master of Science
Paula Borges Costa

**Abstract**

Synchronized swimming is a physically demanding sport that exposes the lower extremity to unusual forces. Currently, limited information exists that outlines the modifiable factors associated with knee pain experienced by synchronized swimmers. **PURPOSE:** This study's aim was to identify the relationship between strength, mobility, movement quality, and pain in collegiate synchronized swimmers. **METHODS:** Sixteen collegiate synchronized swimmers (mean ± SD, 20.5 ± 1.8y; 165.8 ± 5.1cm; 63.8 ± 5.8kg) were tested. Hip musculature isometric strength was measured using an external force transducer. Hip mobility and Q-angle was assessed using a goniometer. Movement quality was determined using the Functional Movement Screen (FMS). Lower extremity pain was assessed using the Knee Outcome Survey – Activities of Daily Living (KOS-ADL). Pearson correlation coefficients were used to determine relationships among the measured variables. Independent T-tests were used to assess differences in scores when comparing pain versus no pain. **RESULTS**: Hip strength ($ADD^R$) was negatively correlated with KOS-ADL ($r = 0.488$, $p = 0.055$). FMS score in the knee pain group was greater than the no pain group ($p < 0.05$). Hip mobility was greater in the pain group ($p < 0.05$), while hip strength was lower in the pain group ($p < 0.05$). Q-angle was not significantly different between groups ($p > 0.05$). Synchronized swimmers demonstrated above normal hip strength, while mobility and Q-angle values were found to be within normal ranges. **CONCLUSION**: Synchronized swimming seems to demand above average hip musculature strength while favoring non hypermobile athletes. Knee pain is a multifactorial condition prevalent among synchronized swimmers. Future studies should investigate optimal mobility and movement quality as it relates to injury risk.

**Keywords**

Knee Pain, Hip Strength, Hip Mobility, Functional Movement Screen, FMS, Q-angle Synchronized Swimming, and Pain Assessment.

This abstract is approved as to form and content

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## Chapter 1: Introduction

### Overview

Synchronized swimming is a unique sport not only because it is an acrobatic event performed in the water, but also for its blended physical demands. Similar to gymnastics and ballet, synchronized swimming is assessed by a committee of trained judges (Mountjoy, 1999; Robertson, Benardot, & Mountjoy, 2014; Sydnor, 1998). While treading water, synchronized swimmers are capable of performing graceful movements in synchrony with each other as well as with the music (Rodríguez-Zamora, et al., 2012). Synchronized swimming first joined the Olympic Games in the summer of 1984 (Mountjoy, 2009). Since then, changes in the criteria have placed higher physical demands on the athletes requiring increased aerobic and anaerobic capacity (Robertson et al., 2014; Schaal et al., 2013). Therefore, synchronized swimmers have been required to perform movements with higher intensities, which exposes their bodies to larger forces, which in turn can lead to greater injury risk exposure.

The synchronized swimmer performs movements in the water without touching the bottom of the pool (Rodríguez-Zamora et al., 2012). The athlete treads water through different ways in order to execute various maneuvers. When upside down, the athlete utilizes her arms through support sculling movements, which enables the legs to move freely above the water (Mountjoy, 2009). The eggbeater kick is another important treading movement utilized to enable to the arms to be used for other purposes (Mountjoy, 2009; Oliveira, Chiu, & Sanders, 2015; Oliveira, Saunders, & Sanders, 2016). Water polo payers also utilize this stroke, in which the lower limbs perform circular motions that looks like a modified whip kick (Mountjoy, 1999, 2009; Oliveira et al., 2015; Oliveira et al., 2016).

Engebretsen et al. (2010) reported that synchronized swimming was one of the safest Olympic sports because there were no in-competition injuries. However, other authors have indicated the incidence of overuse or acute traumatic injuries in the sport, identifying the lower back, shoulders, and knees as the main affected areas (Chu, 1999; Mountjoy, 1999, 2009). Special attention has been drawn to injuries occurring to the knee joint. According to Mountjoy (1999), the eggbeater kick requires an intensive repetitive motion that may lead to pain and discomfort in the knee joint. The eggbeater kick has also been recognized as a contributor to other conditions of the knee: medial collateral ligament strain (Mountjoy, 1999); abnormal track of the patella and patellofemoral pain syndrome (Mountjoy, 2009; Oliveira et al., 2016); chronic overuse injury in the knee, adductor-muscle strain, and tenosynovitis of the extensor longus tendon (Oliveira et al., 2016).

Chu (1999), Mountjoy (1999), and Oliveira et al. (2016) report that patellofemoral pain syndrome is the most frequent condition experienced by eggbeater kickers in part due to the extreme valgus position in which the knee is placed during the eggbeater motion. The eggbeater kick is performed with the hips abducted and flexed with knees also flexed (Homma & Homma, 2005; Oliveira et al., 2016). From that position, hip circumduction in addition to knee flexion and extension allow the athlete to tread water in a variety of speeds. Although the knee joint is highly functional, its complex structure limits the joints ability to sustain many of the excessive forces produced during different athletic activities (Behnke, 2012,).

According to Teyhen et al. (2012), 50-80% of injuries occurring in athletic events involve the lower limbs and are overuse in nature. Oliveira et al. (2016) showed that the eggbeater kick could place additional stress to the knee joint, especially when the athlete is in a stage of fatigue. When hip musculature reaches the fatigue stage, muscular coordination is lost and joint instability might be observed (Oliveira et al., 2016). Others have also shown a relationship between hip muscle strength and knee joint stability in a general population (Bolga, Malone, Umberger, & Uhl, 2008; Cant, Pineux, Pitance, & Feipel, 2014; Hott, Liavaag, Juel, & Brox, 2015). Cant et al. (2014) defends that poor abductor and external rotator strength allows excessive hip adduction and internal rotation motion, and therefore, contributes to patellofemoral joint stress.

It is important to understand how different modifiable factors influence knee pain. The present study proposes to analyze the correlation between knee pain, hip strength, hip mobility, movement quality, and quadriceps-angle (Q-angle). It is hypothesized that the presence of knee pain through the season, during exercise, or during activities of daily living will be associated with poor hip strength, hypermobility, poor movement quality, and greater Q-angle. Finally, the present study aims to identify the strength and mobility profile of collegiate synchronized swimmers. Knee pain affects not only the athlete's performance in the sport, but also their daily functional activities. By understanding what factors are associated with knee pain, professionals assisting synchronized swimmers will be capable of helping these athletes to prevent or reduce the severity of knee pain and enable them to perform better as well as improve their quality of life.

**Hypothesis**

- Hypothesis one: Knee pain (KOS-ADL) is correlated with hip strength, hip mobility, movement quality (FMS score), and Q-angle.
  - Knee pain is positively correlated to hip strength
  - Knee pain is negatively correlated to hip mobility
  - Knee pain is positively correlated to FMS scores

  - Knee pain is negatively correlated to Q-angle

- Hypothesis two: The presence of knee pain throughout the season, during exercise, or during activities of daily living is associated with poor hip musculature strength, hypermobility, poor movement quality, and greater Q-angle.
  - Hip strength within the pain group will be lower than hip strength within the no pain group
  - Hip mobility within the pain group will be greater than hip mobility within the no pain group
  - FMS scores within the pain group will be lower than FMS scores within the no pain group
  - Q-angle within the pain group will be greater than Q-angle within the no pain group
- Research question: What is the current strength and mobility profile of collegiate synchronized swimmers?

**Assumptions**

- Participants will comply with test procedure and give their best effort during tests.
- Participants will honestly complete self-reported questionnaire.

**Delimitation**

- The inclusion criteria focused on female collegiate synchronized swimmers. This excluded other athletes who regularly perform the eggbeater kick such as water polo players since the other components of the sport are different.

- The study only assessed strength in the frontal and transverse plane, disregarding sagittal hip movements. Previous research has established the lack of correlation between sagittal strength and knee pain.

**Limitation**

- Sample size: Collegiate synchronized swimming teams often have a small roster with very few teams in close proximity. Future studies might strive to recruit more than one team.
- Equipment choice: A external force transducer was chosen to assess isometric strength even though there are few published examples utilizing this equipment in this type of application. While there are more studies available utilizing manual assessment, this is not a reliable tool to compare differences between participants. Other studies have used hand-held dynamometers, but these require the tester to be able to exert enough force to ensure maximal isometric contraction without manipulating the results. The external force transducer was chosen for its simplicity of reading maximal isometric contractions without the interference of the tester.
- Questionnaire choice: The self-reported questionnaire (KOS-ADL) was created for athletes in general, and therefore includes questions that do not necessarily apply to the daily activities of a synchronized swimmer.
- Honesty of answers: Each participant was expected to answer the self-reported pain questionnaire with sincerity. However, the ability to ensure such honesty is out of the present study's scope.

**Definitions**

- Bi-articular muscle: muscle which belly crosses two joints.
- Eggbeater kick: kick performed by synchronized swimmers and water polo players that looks like the kitchen tool, eggbeater. Both legs are performing hip circumduction in opposite directions while knees are kept apart and flexed.
- Hip circumduction: circular hip movement combining all three plans of motion.
- Isometric Strength: maximal force applied while the muscle fiber remains in a constant length.
- Knee Outcome Survey – Activities of Daily Living (KOS-ADL): self-reported pain questionnaire, where a lower score is indicative of greater levels of knee pain
- Knee pain: self-reported pain or discomfort experienced in front, behind, or around the patella during functional activities.
- Patellar abnormal track: lack of femur-patella congruence during flexion and extension of the knee.
- Patellofemoral pain syndrome: medically diagnosed condition based on knee pain.
- Range of motion: uninhibited active movement around a joint.

**Abbreviations**

- Q-angle: Quadriceps angle
- FINA: International Federation Association of Swimming
- PFPS: Patellofemoral pain syndrome
- MCL: Medial collateral ligament
- LCL: Lateral collateral ligament
- ACL: Anterior cruciate ligament

- PCL: Posterior cruciate ligament
- T12-L5: 12th thoracic vertebral body through the 5th lumbar vertebral body: origen of the iliopsoas muscle
- IT-band: Iliotibial track
- FMS: Functional movement screen
- FMS score: Composite score resulted from the summation of all 7 functional moment screen tests
- KOS: Knee outcome survey
- ADL: Activities of daily living scale
- IRB: Institutional review board
- AT: Certified athletic trainer
- ASIS: Anterior superior iliac spine
- IR: Internal rotation
- ER: External rotation
- ABD: Abduction
- ADD: Adduction
- SP: Season pain group
- SNP: Season no pain group
- EXP: Exercise pain group
- EXNP: Exercise no pain group
- ADLP: Activities of daily living pain group
- ADLNP: Activities of daily living no pain group
- m: Mobility

- s: Strength
- rs: Relative strength
- R: Right limb
- L: Left limb

## Chapter 2: Literature Review

### Synchronized Swimming

Synchronized Swimming is a unique sport that resembles ballet and gymnastics with the drastic difference of the performance occurring in the water instead of on land (Robertson et al., 2014; Sydnor, 1998). A combination of physical abilities, such as power, endurance, strength, and flexibility, is required to perform acrobatic movements while treading water (Robertson et al., 2014). Without touching the bottom of the pool, athletes propel themselves, as well as each other, out of the water performing incredible routines synchronized to a musical background (Rodríguez-Zamora et al., 2012). The demands of the sport require synchronized swimmers to be both aerobically and anaerobically fit (Robertson et al., 2014).

The history of synchronized swimming dates back to the early 1900s, when Annette Kellerman developed the so-called "ornamental swimming", which was made famous through Esther Williams' movies in the United States (Mountjoy, 1999). Synchronized swimming has been an Olympic sport since 1984, when only solo and duet events were included (Mountjoy, 2009). Since the 2000 Games, the competition format in the Olympiad has changed to include duet and team (8 athletes) performing in front of judges through two modes: technical and free routines (FINA, 2015; Mountjoy, 2009; Robertson, 2014). As determined by the International Federation Association of Swimming (FINA), the collegiate level synchronized swimming competitions incorporates solo, duet, trio, and team events in both technical and free routines.

FINA administers competition's rules and regulations for both the Olympic and the collegiate levels (FINA, 2015). According to Rodríguez-Zamora et al. (2012), each routine lasts between two and five minutes, depending on the mode of each routine. Team events tend to last longer than smaller combinations, such as trios, duets, and solo, while technical routines are generally shorter than free routines (Rodríguez-Zamora et al., 2012). The technical routine is designed to display the athletes' flexibility, strength, skill, power, and control by performing 6-10 elements in a predetermined order (Mountjoy, 2009). Although the combination of elements changes every four years, FINA always includes elements such as arm movements, boosts, figure skills, spins, splits, and vertical twists (Mountjoy, 1999). The free routines have no set elements and are longer in length, consequently allowing for athletes' musical interpretation and individual skill expression (Robertson et al., 2014).

As an artistic sport, synchronized swimming performances are evaluated by a set of judges, who are selected by FINA to ensure standards of competence (Mountjoy, 1999). According to Mountjoy (1999), international events require two panels of seven judges to evaluate the Technical Merit and the Artistic Impression of each routine. Both routines, technical and free, are scored using a rubric-like system that is based on a set of norms and criteria. The main difference among the events (solo, duet, and team) is the percentage of the score attributed by each criterion and each norm. As reported by Mountjoy (1999), both Technical Merit and Artistic Impression comprise three criteria of evaluation. Quality of execution, synchronization with one another and with music, and routine difficulty are the three criteria that compose the Technical Merit. The Artistic Impression criteria are choreography, music interpretation, and manner of presentation. The combination of both technical (35%) and free (65%) routines composes the final competition score in each event (Mountjoy, 1999).

Although the athlete has the freedom to gather the elements and give the routine an artistic touch, there are common movements present on all routines such as eggbeater kick, support scull, and back arching. Mountjoy (2009) describes the eggbeater kick as one of the most important moves in the sport, as it allows the swimmer to maintain her torso above the surface of the water, enabling the arms to move freely in the air. The support scull is also described among important skills because it allows the athlete to support her body in multiple inverted positions, enabling the legs to move freely out of the water. Multiple elements in synchronized swimming involve arching the back at a variety of speeds and angles. The Rocket move is an example of a rapid lumbar arch move that relies on support sculling. During the Rocket move, the athlete powerfully propels her legs above the water performing the splits at the peak of her vertical (Mountjoy, 2009).

Synchronized swimming is a unique sport for it requires the athlete to dominate a variety of physical, artistic, and technical abilities (Schaal et al., 2013). According to Mountjoy (1999), not only must the swimmer master technical skills to perform the elements, but she also needs to be graceful and artistically compose each routine to please the judges. Mountjoy (1999) also points out the need for synchronized swimmers to develop aerobic and anaerobic energy systems. Although the relative short duration of each routine, 2-5min long, the swimmer is consistently propelling herself and her teammates out of the water. According to Baechle & Earle (2008), 2-5min constantly moving primarily challenges the aerobic energy pathway; while extremely high intensity bouts, such as propelling each other out of the water, primarily challenges the anaerobic energy system. Consequently, a synchronized swimmer must master both aerobic and anaerobic energy systems in order to perform on an elite level (Robertson et al., 2014).

Over the years, the demands of the sport have shifted towards maneuvers that are more acrobatic in nature, requiring athletes to increase their training load (Robertson et al., 2014; Schaal et al., 2013). Those changes require the athletes to be faster and more powerful (Rodríguez-Zamora et al., 2012). Therefore, athletes must devote a great amount of time training in and out of the pool. Training regimes often involve two training sessions per day with short recovery interval in between training bouts (Mountjoy, 2009; Schaal, 2013).

According to Mountjoy (2009), elite synchronized swimmers spend about 40 hours per week involved with pool and land based training. A great portion of the training load, roughly 8-10 weekly sessions lasting 2-4hr in duration, is spent in the pool, a an open kinetic chain environment (Mountjoy, 2009). The remainder of weekly hours are devoted to develop and perfect routines or to improve their body's ability to handle the sport. Mountjoy (2009) states that in order to perfect routines, athletes engage in "dry land-drill", an on land rehearsal of the routine, which is very similar to dancing with an excessive usage of the arms that are mimicking the legs movements as well. Synchronized swimmers engage in sport-specific weight training 2-4 times a week incorporating a variety of modes to achieve all the physical demands of the sport: aerobic capacity, anaerobic power, strength, and flexibility (Mountjoy, 1999, 2009). According to Mountjoy (2009), a well-designed training program for synchronized swimming balances fitness development and sport-specific skill acquisition, without ignoring recovery.

During the 2008 Beijing Olympic Games, Engebretsen et al. (2009) informed that synchronized swimming was one of the safest Olympic sports, reporting no in-competition injuries. Injuries in this sport are often attributed to overuse or acute trauma, with the lower back, shoulders, and knees being the most commonly injured areas (Chu, 1999; Mountjoy 1999, 2009). Mountjoy (2009, 1999) observed an excessive overhead use of the arms not only for performance of routines, but also during freestyle swimming used to improve cardiovascular fitness as well as during land drill sessions. Chu (1999) and Mountjoy (2009, 1999) attributed lower back injuries to the frequent twist and turn of the trunk performed in a wide range of speeds and angles. Over use of the knee has been associated with the eggbeater kick. Oliveira &

Sanders (2016) observed poor knee joint stability during the eggbeater kick, especially when executed under fatigue.

Synchronized swimming is a unique sport with unique physical demands. To date, limited scientific information is available focused on this sport. The present study aims to further understand manageable factors influencing knee pain among collegiate synchronized swimmers. Therefore, we propose to identify the athlete's strength, mobility, and quality of movement profile.

**The eggbeater kick**

The eggbeater kick is a complex and unusual stroke utilized in synchronized swimming and water polo to keep their upper body elevated above water (Mountjoy, 2009; Oliveira et al., 2015; Oliveira et al., 2016;). By performing alternating cyclical movements with the lower limbs, the athlete is able to produce constant propulsive forces enabling the body to obtain height above water (Oliveira et al., 2015). In water polo, this kick permits the athlete to pass, shoot, block, or even push an opponent (Oliveira et al., 2016). In synchronized swimming, this stroke is one of the most important moves for it allows the athlete to utilize the arms above the water freely (Mountjoy, 1999, 2009; Schaal et al., 2013).

During the eggbeater kick, the athlete must maintain the knees apart and as high as possible (Homma & Homma, 2005; Oliveira et al., 2016). Oliveira et al. (2016) found that water polo players who were able to maintain greater average hip flexion and hip abduction performed better. Through extreme hip circumduction accompanied by knee flexion-extension, the athlete is able to maintain power while moving in both linear and vertical directions (Chu, 1999). Chu (1999) and Mountjoy (2009) noticed that, during the eggbeater kick, the knee is consistently flexed and exposed to greater valgus forces, which in turn has been associated with increased kne joint stress (Cant et al., 2014).

Mountjoy (2009) warns that both synchronized swimmers and water polo athletes are susceptible to chronic knee overuse injury, perhaps in part due to the use of the eggbeater kick. The eggbeater kick has been associated with chronic strain of the medial collateral ligament (Mountjoy, 1999), abnormal track of the patella or patellofemoral pain syndrome (Mountjoy, 2009; Oliveira et al., 2016); chronic overuse injury in the knee, adductor-muscle strain, and tenosynovitis of the extensor longus tendon (Oliveira et al., 2016). Chu (1999) reports that athletes might complain of knee pain being manifested as subluxation pain around the lateral aspect of the patella or a vague pain on the knee medial side. Oliveira & Sanders (2016) also state that knee injuries are common among athletes who perform eggbeater kick frequently.

While multiple knee injuries are mentioned as possible consequences of the eggbeater kick, a special attention is drawn to patellofemoral pain syndrome (PFPS) (Chu, 1999; Mountjoy, 2009; Oliveira & Sanders, 2016). The concerns involve: (a) the position of extreme valgus in which the knee is kept during the eggbeater (Chu, 1999,), (b) the knee instability caused by fatigued muscles of the hip and knee (Oliveira & Sanders, 2016), and (c) the abnormal tracking of the patella in the trochlear notch of the femur resulted from weak muscles performing the eggbeater kick (Mountjoy, 2009). Therefore, the present study aims to identify muscular imbalances that can place the synchronized swimmer at risk to develop knee pain.

## Anatomy

### Knee Anatomy

The knee is among the largest joints in the body being responsible for weight bearing and locomotion (Behnke, 2012; Dimon, 2008; Ombregt, 2013). The bony formation in conjunction with ligaments and tendons allows the joint to be stable while having some mobility (Ombregt, 2013). The knee is capable of mainly flexion and extension, enabling walking, running, and other means of locomotion. The structures surrounding the knee, such as ligaments, tendons, and muscles, ensure joint stability, preventing excessive movements. However, Ombregt (2013) alerts that several sports events expose the knee to external forces, which may make the structure vulnerable to injury. Behnke (2012) emphasizes that even though the knee is structurally sound, it was not built to sustain the many stressors placed by athletic events.

The tibia and the femur are the bones that composes the knee joint. Several authors refer to the knee as a hinge joint due to its ability to move in the sagittal plane (Dimon, 2008; Ombregt, 2013). The flexion-extension motion is made possible by a roll and glide mechanism. During flexion, the femur rolls backwards and glides forward on the tibia; and the opposite occurs during extension (Ombregt, 2013). Because the roll and glide mechanism happens through an ever-changing axis, Behnke (2012) proposes the knee joint to be classified as a modified hinge joint. Moreover, the knee joint is also capable of slightly move in the transverse plane when flexed (Behnke, 2012; Ombregt, 2013).

The articulation between femur and tibia is possible through a combination of characteristics and structures such as the wide articular surface of both bones, the fibrocartilaginous cushion, and the capsular ligament. The distal end of the femur enlarges forming two wheel-like structures (Behnke, 2012; Ombregt, 2013). Ombregt (2013) describes these flared out structures, the femoral condyles, as a double wheel connected by a junction, the intercondylar notch. The medial femoral condyle projects slightly more distally (Behnke, 2012) while the greater prominence of the lateral condyle restricts lateral sliding of the patella (Ombregt, 2013). The femoral condyles sits on the tibial condyles. Although the tibial condyles are flatter and not congruent to the femoral condyles, Ombregt (2013) certifies that the congruence is achieved by means of a pair of cartilaginous discs, the menisci. These semilunar-shaped discs not only deepen the condylar surface at the tibia (Behnke, 2012; Dimon, 2008), but also assist with shock absorption, weight distribution through the tibia, and knee motion coordination (Dimon, 2008; Ombregt, 2013). According to Ombregt (2013), the menisci are sensitive to trauma for they have little healing ability and no pain-sensitive structures. Minimal healing is possible through synovial fluid absorption (Dimon, 2008; Ombregt, 2013).

As other synovial joints, knee joint stability in ensured by ligaments composing the articular capsule. Behnke (2012) assures differently than other synovial capsules, the capsular ligament at the knee is composed of portions of ligaments not particular to the capsule and fibrous expansions of other structures. Another important structure that composes the capsule is the patella, the largest sesamoid bone in the body. Although a bone, the patella or kneecap has no connections to other bones (Behnke, 2012). Instead, the kneecap lies within the quadriceps tendon, which inserts at the tibial tuberosity and composes the anterior articular capsule (Behnke, 2012; Dimon, 2008; Ombregt, 2013). The main function of the patella is to act like a pulley changing the pulling angle and allowing greater rotatory force to be applied by the quadriceps muscle group (Behnke, 2012; Dimon, 2008; Ombregt, 2013). The patella is most congruent with the femur, but during flexion and extension, it acts as one structure with the tibia (Ombregt, 2013). Although the lack of direct connection between femur and patella, these bones act collectively forming the patellofemoral joint (Cant et al., 2014). Together ligaments and menisci provide static stability while the tendons and muscles ensure dynamic stability to the knee joint (Ombregt, 2013).

The ligaments surrounding the knee prevent undesirable movements while assisting with knee stability. On either side of the knee, the collateral ligaments prevent motion in the frontal plane (Behnke, 2012). The medial collateral ligament (MCL), which is part of the capsular ligament, runs from the medial condyle of the femur and attaches just behind and under the semitendinosus tendon at the medial aspect of the medial condyle of the tibia (Behnke, 2012; Ombregt, 2013). According to Ombregt (2013), some fibers of the MCL attach to the medial meniscus, which is an important to note when dealing with meniscus tear. On the other side lies the lateral collateral ligament (LCL), which is not part of the capsule ligament and does not connect to the meniscus (Behnke, 2012). The LCL connects the lateral condyle of the femur to the head of the fibula (Behnke, 2012; Ombregt, 2013). Thought not part of the knee capsule, Ombregt (2013) brings to attention that the LCL is part of a strong lateral stabilizer complex called lateral quadruple complex. This complex is composed by the biceps tendon, the iliotibial tract, and the popliteus (Ombregt, 2013). The MCL and the LCL support the knee by providing frontal plan stability and therefore preventing excessive valgus and varus forces, respectively (Behnke, 2012; Ombregt, 2013).

In the middle of the knee joint lie two cruciate ligaments, named for how they cross each other (Dimon, 2008). The anterior cruciate ligament (ACL), the most anterior of the two, rises from the anterior intercondylar eminence of the tibia, between the menisci anterior horns, and travels obliquely, laterally and posteriorly, to attach at the internal aspect of the lateral condyle of the femur (Behnke, 2012; Ombregt, 2013). The posterior cruciate ligament (PCL), in turn, attaches the posterior intercondylar eminence of the tibia to the lateral surface of the medial femoral condyle (Behnke, 2012; Ombregt, 2013). Both the ACL and the PCL play important role in knee stability. Behnke (2012) mentions that the ACL, in conjunction with posterior muscles, prevents hyperextension of the normal knee. Ombregt (2013) stresses that the PCL is twice as strong as the ACL, but in contrast, it is the tightest at mid-ranges. The cruciate ligaments ensure proper gliding movements of the femur during flexion and extension of the knee. According to Ombregt (2013), during flexion, the ACL pulls the femur forward and during extension, the PCL pulls this same bone backwards while the tibial rolls in opposite direction. In addition, the ACL also limits external rotation and varus positioning of the tibia (Ombregt, 2013). Behnke (2012) warns that excessive squatting places the PCL in stress.

Stability of the knee is further acquired through irregular ligaments in the posterior and anterior portions of the joint. Posteriorly, the knee is secure by the oblique popliteal and the arcuate popliteal ligaments (Behnke, 2012; Ombregt, 2013). The oblique popliteal is an extension of the semimembranosus tendon running from the lateral femoral condyle to the medial tibial condyle (Behnke, 2012; Ombregt, 2013). The arcuate popliteal crosses the knee in the opposite direction from the fibular head to the medial femoral condyle (Behnke, 2012; Ombregt, 2013). The main anterior ligament isn't a true ligament, the patellar ligament is part of the quadriceps tendon and embeds the patella, as discussed previously (Behnke, 2012).

In summary, knee stability is possible through the combination of several features of the knee. Structural stability is achieved through the manner in which the femur sits on the top of the tibia. Secondly, the menisci further ensures femur-tibia congruency. Additionally, several ligaments involve the knee in a tight sleeve, reinforcing stability. Although the joint is highly functional, Behnke (2012) alerts that many athletic events exposes the knee to excessive forces. Dynamic knee stability is achieved through the coordination of several muscle surrounding the knee joint. Muscles acting on the knees are often bi-articular, acting on the hips as well;

therefore, the present study proposes to review the knee musculature in conjunction with the hip musculature investigating for modifiable factors influencing knee pain.

**Hip Anatomy**

The hip is a unique joint for its shape, function, and range of motion. Dimon (2008) compares the hip joint to the shoulder joint through several aspects. Both joints are synovial joints with three degrees of freedom and they both connect the limbs (or peripheral skeleton) to the axial skeleton. Dimon (2008) suggests that the main difference is the role that each joint has in the body. The shoulder girdle allows mobility for the upper limbs to be use for manipulation. The hip joint, in contrast, has a main purpose of locomotion transferring the weight of the body down through the legs into the ground while absorbing shock from legs (Dimon, 2008). Without a true articulation, the scapula lies on top of the spine, allowing the upper limbs more freedom for movements (Dimon, 2008). On the other hand, Dimon (2008) points out that the connection between the spine and the lower limbs occurs through a true joint, the iliacsacrum joint. Therefore, the hip joint, when compared to the shoulder joint, has a limited range of motion. However, the ability to bear weight creates an important link between axial and peripheral skeleton.

The hip joint not only has three degrees of freedom for movement, but it also supports the body weight through upright position and locomotion (Byrne, Mulhall, & Baker, 2010; Dimon, 2008). The hip joint serves as the connection between axial and peripheral skeleton, being responsible to transfer energy generated from the ground up, as well as from the trunk, head and neck, and arms downwards (Byrne et al., 2010). Although not as freely as the shoulder joint, the hip joint is capable of producing movements in all three plans of motion: sagittal, frontal, and transverse. Such a wide versatility requires surrounding structures to ensure stability such as ligaments, muscles and tendons. Byrne et al. (2010) defends that the stability along with the range of motion expressed by the hip joint allows it to be of great importance in athletic events.

The hip joint is a rather versatile joint. Byrne et al. (2010) emphasize four features of the hip that characterizes it as a synovial joint: (a) joint cavity, (b) articular cartilage on top of the joint surface, (c) synovial fluid produced by synovial membrane, and (d) a ligament capsule involving the joint. The joint cavity is created through bone shapes and ligament lining (Byrne et al., 2010). The hip joint is a ball-and-socket synovial joint formed by a cup-shape acetabulum and an oval-shaped femoral head surrounded by a fibrous sleeve lining, as described (Ombregt, 2013). The acetabulum, the socket portion of the joint, is composed of three bones: ischium, pubis, and ilium (Byrne et al., 2010). According to Byrne et al. (2010), the bones forming the acetabulum start to fuse around the age of 14-16, and achieve complete fusion by 23 years old. Although these three bones are part of the appendicular skeleton, they are located proximally in relation to the femur, which contains the ball portion of the joint, the femoral head (Byrne et al., 2010).

The joint surfaces of the acetabulum as well as the femoral head are covered by articular cartilage, which houses a synovial covered fat pad (Byrne et al., 2010; Ombregt, 2013). The femoral head is spheroid and fits almost perfectly in the acetabulum cup (Ombregt, 2013). The acetabular labrum expands from the articular surface of the acetabulum and deepens the socket where the femoral head sits, providing greater stability and shock absorption to the joint. Byrne et al. (2010) emphasizes that even though the acetabular labrum at the hip does not provide as much stability to the joint as the glenoid labrum does to the shoulder, it still serves that purpose.

The hip joint capsule is a cylindrical sleeve composed by ligaments connecting the acetabulum and the femoral neck through multiple angles (Byrne et al., 2010; Dimon, 2008;

Ombregt, 2013). Three powerful ligaments are critical to the stability of the hip joint while two others are critical assistants. According to Ombregt (2013), on the anterior side, the femoral ligament and the pubofemoral ligament together resemble the letter “Z”. On the posterior side, the ischiofemoral ligament completes the sleeve surrounding the hip joint. These three powerful ligaments supports the joint movements allowing stability and range of motion. Two other ligaments, although through a small contribution, assist to the stability of the hip (Ombregt, 2013). The ligamentum teres links the central portion of the femoral head to the acetabulum notch. The second is the angular ligament, which encircles the femoral neck like a buttonhole but has little stability role (Ombregt, 2013).

The bone anatomy, as well as the capsule composition, support hip stability and versatility through a wide range of motion. The twenty-two muscles surrounding the hip further empower all three degrees of freedom (flexion-extension, abduction-adduction, internal-external rotation) while further ensuring stability. The present review will analyze the muscular anatomy of the hip in conjunction with the knee, since several muscles acting on the hips are bi-articular, acting on the knees as well. One of the aims of the present study is to identify hip muscles imbalances correlated to knee pain.

**The muscular anatomy of the Knees and Hips**

The majority of the muscles acting at the knee joint are multi-articular muscles crossing more than one joint (Behnke, 2012; Dimon, 2008; Ombregt, 2013). The aim of the present study is to identify correlations among hip strength and knee pain. Therefore, an emphasis will be placed on muscles of the upper thigh that acts on the hip and knee, with a focus on the anatomical and physiological characteristics of such muscles. There are several approaches to study the muscles acting on the hip and knee joint; one is to separate into groups according to their main action (flexion, extension, abduction, adduction, internal rotation, external rotation). The present study will first group muscles according to their actions at the knee, and then will study other muscles according to their actions at the hip. It is important to keep in mind that a muscle might have secondary actions possible only at specific joint positioning due to their bi-articular characteristic (Behnke, 2012).

*Knee Extension*

As discussed previously, the knee is a modified hinge joint, capable of flexion-extension and slight internal and external rotation when the knee is flexed (Ombregt, 2013). The main knee extensor is the quadriceps muscle group which is composed by four muscles, that share a common insertion tendon: rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius (Behnke, 2012; Dimon, 2008; Ombregt, 2013). Different authors refer to this tendon through different names: common tendon (Dimon, 2008), patellar ligament (Behnke, 2012), quadriceps tendon (Ombregt, 2013). Nevertheless, all of the above-mentioned nomenclatures describe the fibrous structure that connects all four quadriceps muscles to the anterior tibial tuberosity while embedding the patellar bone. The mechanical advantage of this embedded bone was described in the knee anatomy section of this review as an important pulley that changes the acting angle allowing greater rotatory force (Behnke, 2012; Dimon, 2008; Ombregt, 2013). The patella has no ligament connecting it to any other bone; therefore, its relative position is obtained through muscle actions. (Cant et al., 2014)

The rectus femoris is the most superficial muscle of the anterior thigh and the only quadriceps muscle that crosses two joints, the hip and the knee (Behnke, 2012). The rectus femoris originates at the ilium in two places: the anterior inferior iliac spine and just above the acetabulum (Behnke, 2012; Dimon, 2008). Due to its insertion at the tibial tuberosity and origin at anterior inferior iliac spine, the rectus femoris acts on the hip as a flexor and on the knee as an extensor (Behnke, 2012, p.253).

Each vastus muscle originates in the proximal femur and inserts at the tibial tuberosity through the patellar ligament; therefore, mainly acting as knee extensors (Behnke, 2012; Dimon, 2008; Ombregt, 2013). The vastus medialis runs from the medial linea aspera to the medial border of the patella (Behnke, 2012). The vastus lateralis is described as the largest of the three vastus raising from the proximal half of linea aspera, intertrochanteric line, and greater trochanter and attaching to the lateral border of the patella (Behnke, 2012). The vastus intermedius, which lies underneath the recuts femoris, originates from the proximal two-thirds of the anterior surface of the femur and inserts in the inferior surface of the patella (Behnke, 2012). According to Ombregt (2013), the vastus intermedius has deep fibers that attaches to the superior capsule pulling the loose capsule away from the joint and preventing impingement during knee action. With the exception of the rectus femoris, these three quadriceps act exclusively as knee extensors.

Another, though weak, knee extensors group are the gluteus maximus and the tensor fascia latae, both of which act through the iliotibial tract (Ombregt, 2013). The iliotibial tract, also referred to as IT-band, is a strong band that thickens the lateral side of the fascia lata and inserts at the inferior anterior aspect of the lateral tibial condyle (Ombregt, 2013). Both the gluteus maximus and the tensor fascia lata insert into this band, and therefore acting on the knee as weak extensor. In fact, the knee angulation changes the relative position of the iliotibial tract to the knee (Behnke, 2012). Behnke (2012) emphasizes that the iliotibial tract is anterior to the knee joint up to 15° of knee flexion; therefore, acting as a knee extensor. However, when the knee is flexed pass 15°, the iliotibial tract is in a relative position posterior to the knee joint, therefore acting as a knee flexor. Regardless of the action, the gluteus maximus and the tensor fascia lata have the main function to stabilize the knee by the means of the iliotibial tract (Dimon, 2008; Ombregt, 2013). Even though their main function at the knee is stabilization, both gluteus maximus and tensor of the fascia lata have other purposes at the hip, which are discussed later.

*Knee Flexion*

As noted above, few muscles are responsible for knee extension: the quadriceps group and the two muscles acting through the iliotibial tract. On the other hand, there are far more muscles responsible for knee flexion. The knee joint was described as a modified hinge joint that when flexed is able to slightly rotate internally and externally. Therefore, some muscles that flex the knee also internally or externally rotate the lower leg. In addition, some of these muscles are bi-articular, acting at the hips as well.

The hamstring muscle group, located in the posterior thigh, is composed of three muscles: biceps femoris, semitendinosus, and semimembranosus (Behnke, 2012). All three muscles originate in the ischial tuberosity, cross the hip joint and the knee joint, and insert in the tibia or the fibula (Behnke, 2012; Dimon, 2008; Ombregt, 2013). The biceps femoris is the most lateral of the hamstring muscle, inserting at the lateral condyle of the tibia (Behnke, 2012; Dimon, 2008). Its origin is also distinct in the fact that it has an additional attachment at the lateral aspect of the linea aspera (Behnke, 2012). Ombregt (2013) and Behnke (2012) note that due to its attachments, the biceps femoris is a strong knee flexor and hip extensor and is able to assist with knee external rotation (when knee is flexed) and with hip adduction and external rotation.

The semitendinosus and the semimembranosus, the other two hamstrings muscles, are very similar. As described by Dimon (2008), both muscles originate at the ischial tuberosity and insert at the medial side of the tibia, with the main difference being the tendon length. The semitendinosus has a longer tendon that runs superficially to the semimembranosus and inserts under and in front of the medial condyle at the pes-anserinus (Dimon, 2008; Ombregt, 2013). The semimembranosus, in turn, inserts in the posterior aspect of the tibia (Behnke, 2012; Dimon, 2008; Ombregt, 2013), and some of its fascicles attach to the posterior edge of the medial meniscus (Ombregt, 2013). Both medial hamstrings are capable of knee flexion and hip extension (Behnke, 2012; Dimon, 2008; Ombregt, 2013). Behnke (2012) describes their secondary function as assisting knee and hip internal rotation as well as hip adduction. Ombregt (2013) further discusses the efficiency of all three hamstrings as hip extensors being dependent on the position (extension) of the knee.

Assisting the hamstrings with knee flexion are four other muscles: sartorius, gracilis, popliteus, and gastrocnemius (Behnke, 2012; Dimon, 2008; Ombregt, 2013). The sartorius and gracilis are bi-articular muscles that cross the hip and knee joint. The gastrocnemius is also bi-articular since it crosses the knee and the ankle joint (Behnke, 2012; Dimon, 2008; Ombregt, 2013). Dimon (2008) and Behnke (2012) acknowledge the sartorius as the longest muscle in the body, running downward from the anterior superior iliac spine to the pes-anserinus located in the medial aspect of the proximal tibia. Although Ombregt (2013) describes the sartorius as mainly hip flexor, Behnke (2012) points out that this muscle also has secondary actions to flex and internally rotate at the knee, as well as abduct and externally rotate at the hip. The gracilis, another knee flexor, is often described as a hip adductor (Behnke, 2012; Ombregt, 2013). According to Ombregt (2013), the gracilis is the only adductor of the hip that is bi-articular, running between the inferior surface of the pubic symphysis and the pes-anserinus of the tibia. In addition to knee flexion and hip adduction, the gracilis is also able to internally rotate the knee and flex the hip (Behnke, 2012; Ombregt, 2013).

The popliteus is the only knee flexor that is mono-articular. Ombregt (2013) emphases the proximal attachment of the popliteus muscle for its role in knee stability during movement, which is similar to the static function of the PCL. The popliteus muscles lies dorsally to the knee joint. Its fibers run diagonally from the lateral femoral condyle to insert broadly at the proximal third of the posterior aspect of the tibia (Behnke, 2012; Ombregt, 2013). The popliteus muscle functions as knee stabilizer during movements such as squats as well as knee internal rotator (Behnke, 2012; Ombregt, 2013). Additionally, this muscle also assists with capsular and meniscus repositioning (Behnke, 2012; Ombregt, 2013).

The gastrocnemius, another weak knee flexor, crosses the ankle joint in addition to the knee joint (Ombregt, 2013). As described by Behnke (2012), the gastrocnemius raises from the posterior aspect of each femoral condyle and inserts through a strong tendon at the calcaneus. Ombregt (2013) emphasizes that plantar flexion and heel inversion are the main action of the gastrocnemius. However, this muscle plays an important role in joint stability during dynamic movement (Behnke, 2012; Ombregt, 2013).

*Hip Flexion*

The main hip flexor muscle is the iliopsoas, which is a combination of the psoas major, psoas minor, and iliacus (Ombregt, 2013). The origin of each muscle is spread along the T12-L5 vertebral bodies, the superior two-thirds of the bony iliac fossa, and the iliolumbar ventral sacroiliac ligaments (Behnke, 2012). The common insertion of the three muscles composing the iliopsoas is the lesser trochanter (Behnke, 2012; Ombregt, 2013). The iliopsoas also assists with adduction and external rotation of the hip.

Additional muscles assist the iliopsoas with hip flexion. Some of them have already been discussed previously, the sartorius, the recto femoris, and the tensor fascia lata. The last one was only briefly discussed as its influence at the knee by the means of the IT-band. Although a small muscle, the tensor fascia lata is capable of many actions. It originates from the outer surface of the anterior superior iliac spine and joins the gluteus maximus forming the IT-band to insert at the lateral tibial condyle (Behnke, 2012; Ombregt, 2013). At the hip joint, the tensor fascia lata flexes, abducts, and internally rotates the lower leg; while at the knee it acts mainly as a joint stabilizer (Behnke, 2012; Ombregt, 2013). The pectineus, adductor longus and brevis, and the most anterior fibers of the adductor magnus and the glutei (medius and minimus) are also active during hip flexion, though only though accessory function.

*Hip Extension*

Among the hip extensors, the gluteus maximus is the most important being assisted by the hamstrings, which has previously been discussed. The gluteus maximus originates from the posterior aspect of the ilium, sacrum, and coccyx and runs lateral caudal (Behnke, 2012; Dimon, 2008; Ombregt, 2013). Ombregt (2013) describes the gluteus maximus insertion as three-quarters of the muscle joins the tensor fascia lata, as discussed earlier, and the remaining attaches to the gluteal tuberosity of the femur. Its insertion points distinguish the gluteus maximus' ability to strongly extend, abduct (upper fiber), and adduct and externally rotate (lower fibers) the hip (Ombregt, 2013). According to Ombregt (2013), the gluteus maximus is inactive during standing and during stooping. However, it becomes active in conjunction with the hamstrings when raising the trunk from a forward bent at the hips (Ombregt, 2013).

*Hip Abduction*

The major hip abductor is the gluteus medius, which is assisted by gluteus minimus, the tensor fascia lata and the upper fibers of the gluteus maximus (Behnke, 2012; Ombregt, 2013). The gluteus medius resembles an upside down triangle with the base being the origin at the external surface of the ilium and the tip being the insertion at the lateral aspect of the greater trochanter (Behnke, 2012). The gluteus medius runs deep underneath the tensor fascia lata and the gluteus maximus (Ombregt, 2013). Together, these muscles stabilize the pelvis in the transverse plan, which is essential for normal walking as well as for standing on one leg. The gluteus minimus, which also assists with pelvic stabilization, runs deeper than the gluteus medius (Ombregt, 2013). They originate from the gluteal surface of the ilium to insert at the anterior aspect of the greater trochanter (Behnke, 2012). According to Ombregt (2013), the architecture of the tensor fascia lata and the gluteus maximus inserting at the iliotibial tract resembles a 'hip deltoid'. Such insertion enables these muscles to influence the stability of the knee joint during erect posture (Ombregt, 2013).

*Hip Adduction*

The adductor magnus, adductor longus, gracilis, external obturator, pectineus, quadratus femoris, semimembranosus, semitendinosus, and biceps femoris together compose the hip adductor group. According to Ombregt (2013), the adductor magnus is the most powerful hip adductor, though it has little clinical importance. On the other hand, the adductor longus has clinical significance for it is more commonly strained (Ombregt, 2013). The adductor longus also assists with hip flexion running from the anterior aspect of the pubis to insert in the medial aspect of the femur at the linea aspera (Behnke, 2012). Another important hip adductor is the gracilis, which is the most superficial muscle of this group and was discussed earlier. The quadratus femoris along with the pectineus assist in hip external rotation. The quadratus femoris is a flat muscle, which arises from the lateral border of the ischium tuberosity and inserts near the intertrochanteric crest of the femur (Behnke, 2012). Other hip external rotator muscles are the obturator muscles, the piriformis, the gluteus maximus, and the posterior fibers of the adductor magnus and of the gluteus medius. According to Ombregt (2013), these muscles are clinically unimportant, and therefore, little information is available on their relationship with movement. Ombregt (2013) emphasizes the relationship between hip adductors and abdominal muscles noting the co-occurrence of adductor tendinitis and rectus abdominus tendinitis. Nonetheless, hip adductors influence the positioning of the femur during dynamic movement, and therefore can have effects on knee pain.

The musculature of the hips and knees assist joint stability and empowers movements through the range of motion. Hott et al. (2015) suggest that hip muscle weakness is correlated with knee joint instability. Oliveira et al. (2016) affirms that fatigue causes lack of muscle coordination leading to knee joint instability. Hip strength is a modifiable variable shown to be related to knee pain. The present study proposes to investigate the strength profile of collegiate synchronized swimmers as well as to identify if a correlation between hip strength and knee pain is existent in this population.

**Injuries of the Knee Related to Synchronized Swimming**

As discussed earlier, the knee is a structurally sound joint that plays a huge role in locomotion. The bones forming the knee are congruent to each other with the assistance of the menisci (Ombregt, 2013). Both capsular and extra capsular ligaments as well as tendons are components that ensure knee stability. Although the knee is a highly functional joint, it is susceptible to injuries. Several factors including muscle imbalances and anatomical particularities contribute to injury risk (Boling, et al., 2009; Hott et al., 2015; Ireland, Willson, Ballantyne, & Davis, 2003). Moreover, sporting activities often expose the knee to external forces that overloads the joint in a way that might present risk for injuries (Ombregt, 2013; Behnke, 2012).

Synchronized swimming, although an aquatic event, exposes the knee to external forces as anecdotally observed by Mountjoy (2009). Oliveira et al. (2016) suggested that the excessive repetitive use of the eggbeater kick, executed by synchronized swimmers and water polo players, exposes the lower-limb to external forces. Therefore, the knee becomes vulnerable to injury risk such as patellofemoral pain syndrome (PFPS), chronic overuse injury in the knee, adductor-muscle strains, and tenosynovitis of the extensor longus tendon (Oliveira et al., 2016) Especial attention has been drawn to PFPS and chronic overuse injuries. This conditions are commonly perceived as knee pain or discomfort (Boling et al., 2009). Pain is a self-reported mechanism through which the body communicates that something is not right (Hasudungan, 2013). Therefore, pain is a perceived condition that precedes clinical diagnoses, while injury is a clinical diagnose (Cant et al., 2014). According to Santos et al. (2015), knee pain limits performance of functional activities in addition to sports activities. For the purpose of the present study, pain will be the main investigated aspect instead of injury because of its self-reported nature.

PFPS is not particular to synchronized swimmers and water polo athletes. According to Boling et al. (2009), one in four active adults experience PFPS Although it has high prevalence, PFPS etiology is perplex and clinically challenging (Souza & Powers, 2009, p.12). Bolgla et al. (2008) refers to this condition as an orthopedic enigma for its vague and controversial etiology. PFPS is described as antero, retro or peripatellar pain or discomfort during functional activities (Bolgla et al., 2008; Boling et al., 2009; Cant et al., 2014; Hott et al., 2015; Santos, Oliveira, Ocarino, Holt, & Fonseca, 2015; Teyhen, et al., 2012). These activities may include those of the daily living like walking, standing, or sitting. Pain and discomfort can also occur during sporting activities such as squatting, running, and jumping (Bolgla et al., 2008; Cant et al., 2014; Santos et al., 2015; Hott et al., 2015).

Several authors support the theory that PFPS is a multifactorial complex condition (Bolgla et al., 2008; Boling et al., 2009; Cant et al., 2014; Hott et al., 2015; Santos, Oliveira, Ocarino, Holt, & Fonseca, 2015; Teyhen, et al., 2012; Ireland et al., 2003). There seems to be a trend among the theories of PFPS etiology. Knee pain is thought to be caused by abnormal patellar tracking or malalignment of the patella on the trochlear groove at the femur (Bolgla et al., 2008; Hott et al., 2015; Ireland et al., 2003). Some hypothesis try to explain the abnormal tracking of the patella through anatomical differences such as Q-angle and lower extremities structural abnormalities (Bolgla et al., 2008; Boling et al., 2009; Cant et al., 2014). Other existing hypothesis link the dynamic movements of the adjacent joints to the knee to the malalignment of the patellofemoral joint (Boling et al., 2009; Hott et al., 2015; Ireland et al., 2003). Some hypothesis mention that the strength of muscles surrounding adjacent joints influence the knee kinematics, affecting the PFPS as well (Boling et al., 2009; Cant et al., 2014). Although there are several theories for the causes of such condition, the actual cause of patellofemoral pain is not clear.

The Q-angle is defined as the acute angle formed between the quadriceps femoris muscle and the patellar tendon (Bolgla et al., 2008; Türkmen et al., 2015). According to Bolgla et al. (2008), Boling et al. (2009), and Cant et al. (2014), greater Q-angles exposes the knee to greater stresse due to an increase in lateral tracking of the patella. Woodland & Francis (1992) reports that women generally have larger Q-angle when compared to men, but a normal Q-angle for both genders range from 8° to 17°. Although the static measurement of Q-angle can be a risk factor for PFPS, Ireland et al. (2003) suggest that the Q-angle during movement should also be considered as a risk factor. In addition, Santos et al. (2015) advocate that muscle weakness may result in altered biomechanics.

The dynamic relative positioning of the joints is another hypothesized risk factor for developing PFPS (Boling et al., 2009; Hott et al., 2015; Ireland et al., 2003). The knee is in between the hip and the ankle joint (Ombregt, 2013). Ireland et al. (2003) propose that both of those adjacent joints along with their musculature have the ability to affect the knee joint kinematics, the hip being a proximal factor and the ankle being a distal factor. According to Tyler et al. (2006), the influence of the hip musculature and kinematics on anterior knee pain was first identified in 1976. Since then, there has been an increase in focus on hip strengthening to treat knee pain (Cant et al., 2014; Hott et al., 2015).

According to Cant et al. (2014), lack of hip muscular control may increase hip adduction or internal rotation, increasing Q-angle during dynamic movements, and therefore, increasing patellofemoral joint stress. Bolgla et al. (2008) suggest that lack of hip abduction and external rotation strength may specifically decrease the ability to control valgus forces. Stoll et al. (2000) presents normative values for maximal isometric strength assessed with a pull gauge. According to their study, hip abduction of the left leg is normally 188N and the right leg is 193N, hip external rotation of the left leg is usually 80N and the right leg is 83N (Table 2).

Ireland et al. (2003) propose that distal factors, such as foot pronation, might also have effects in the knee joint. Prolonged foot pronation, observed during gate walk, places the tibia in an internally rotate position, requiring the femur to rotate internally in order to maintain congruency with the patella (Ireland et al., 2003). The result of all these accommodations is an increased Q-angle; and therefore, increased patellofemoral joint stress (Ireland et al., 2003; Boling et al., 2009).

Several authors suggest that women are more likely to develop PFPS than men are (Cant et al., 2014; Hott et al., 2015; Ireland et al., 2003). Cant et al. (2014) reported a prevalence rate of 12-13% in women between 18-35 years of age. Hott et al. (2015) attributes such likelihood to an increased Q-angle that sometimes is accompanied with lack of hip musculature strength. Women with PFPS were found to have weaker hip abduction and external rotation when compared with healthy control (Hott et al., 2015, p.2).

As highlighted by Boling et al. (2009), the PFPS is a multifactorial problem with non-modifiable risk factors such as anatomical abnormalities. However, research is needed to identify modifiable risk factors in order to assist the active population, including synchronized swimmers, to avoid PFPS. Boling et al. (2009) and Cant et al. (2014) suggest that altered kinematics and kinetics during functional tasks might be caused by poor hip and knee musculature strength, which in turn can lead to the malalignment of the patella on the femoral trochlear.

Hott et al. (2015) point out that open kinetic chain activities increases the stress placed on the knee joint. Open kinetic chain exercises are those in which the terminal joint is free to move, allowing greater concentration on an isolated joint or muscle (Baechle & Earle, 2008). Movements performed in the water are therefore classified as open kinetic chain movements. Although no significance in patellar displacement was found in PFPS patients performing open kinetic chain activities, Felicio et al. (2014) alerts that such exercises can lead to an increase in lateral patellar displacement and therefore increase patellofemoral joint stress. The eggbeater kick performed by synchronized swimmers is an open kinetic chain activity; therefore, the knee is exposed to forces that can lead to an increase in patellofemoral joint stress.

Cant et al. (2014) reported that subjects with PFPS presented strength deficits in hip abduction, extension, flexion, and external rotation when compared with healthy control. On the same review, Cant et al. (2014) reported no deficit in hip adduction and internal rotation on subjects with PFPS when compared with their healthy counterpart. Souza & Powers (2009) suggests that excessive internal rotation and adduction contributes to patellofemoral joint stress. Page et al. (2010) even bring to the discussion the impact of a shortened IT-band, which might contribute to patellar tracking alterations. Souza & Powers (2009) confirm that lack of hip muscular control may allow excessive hip motion in the frontal and transverse planes, which in turn, places greater stress in the patellofemoral joint.

Movement functionality has been discussed in a variety of settings (Chimera, Smith, & Warren, 2015; Teyhen et al., 2012). Cook et al. (2014a, 2014b) suggest that lack of functional movement indicates weakness and lack of coordination that might predispose an athlete to injury. Chimera et al. (2015) indicates that non-contact injuries might be a result of failure in muscular coordination during high velocity movements and momentary loss of normal protective support. The lack of movement efficiency, kinetic chain coordination, and contralateral muscular balances have been thought to be intrinsic risks for injury (Chimera et al., 2015; Chorba, Chorba, Bouillon, Overmyer, & Landis, 2010; Cook et al., 2014a, 2014b; Teyhen et al., 2012).

Therefore, the present study proposes to analyze the peak isometric strength of the hip and knee musculature using an external force transducer (Load Cell), the hip internal and external rotation mobility using a goniometer, and the muscular coordination during functional movement using the Functional Movement screen (FMS). It is hypothesized that synchronized swimmers who experience knee pain have poor hip musculature strength, especially of the abduction and external rotation. These athletes might also have greater Q-angle and transverse plane range of motion, especially internally. Moreover, those who experience pain might present lower movement coordination and score lower in the FMS. The occurrence of knee injuries in athletes who frequently perform the eggbeater kick is evident. It is important to understand how to prevent such injuries as they potentially harm the athletes' ability to perform their sports as well as activities of daily living.

**Instrumentation**

*Goniometer for Q-angle*

Quadriceps angle (Q-angle) is the acute angle formed by two lines of pull derived from the quadriceps femoris muscle and the patellar tendon (Bolgla et al., 2008; Türkmen et al., 2015). The Q-angle is clinically assessed using a goniometer to measure the angle formed between the anterior superior iliac spine to the center of the patella and the center of the patella to the tibial tuberosity (Bolgla et al., 2008; Mizuno et al., 2001; Türkmen et al., 2015; Woodland & Francis, 1992, p.208). Woodland & Francis (1992) reported normal values for both genders to range from 8° to 17°, with women consistently having higher values due to their wider pelvic base. Clinically high Q-angle has been suggested to be greater than 19° (Woodland & Francis, 1992).

There are several methods to measure Q-angle varying on body position (standing, sitting, or laying supine) as well as on knee angle (fully extended or slightly flexed on different angles) (Türkmen et al., 2015; Woodland & Francis, 1992,). Woodland & Francis (1992) demonstrated that greater Q-angle measurements are acquired when subjects are in a standing position. When compared to supine position, standing measurements were 1.2° greater among the female population Woodland & Francis (1992) reported reliability coefficient to be 0.81 on supine position.

*Goniometer for hip range of motion*

Active range of motion is defined by the American Academy of Orthopedic Surgeons as the movement available at a join ("Glossary", n.d.) and is measured using a goniometer (Gajdosik & Bohannon, 1987; Simoneau, Hoenig, & Papanek, 1998). Hip internal and external mobility is often measured in the clinical setting to quantify joint mobility aiming to track patients' progress (Simoneau et al., 1998). Gajdosik & Bohannon (1987) recommend not to use range of motion as an indicator of muscular tightness, as there are more factors contributing to such condition.

Hip range of motion can be measured in a variety of positions such as laying or seated with validity and reliability being reported on both positions (Gajdosik & Bohannon, 1987; Simoneau et al., 1998). The present study will assess hip mobility in a supine position. According to the American Academy of Orthopedic Surgeons, both internal and external rotation normally range from zero to 45°.

*Functional Movement Screen (FMS)*

The Functional Movement Screen (FMS) was developed to assess one's ability to move through basic movement patterns that challenge the body's proprioceptive abilities (Cook et al., 2014a). Cook et al. (2014a) defined proprioception as the body's system to understand joint placement and to communicate along the kinetic chain (proximal-distal segments) in order to produce any human movement. Chimera et al. (2015), Cook et al. (2014a, 2014b), Teyhen et al. (2012), advocate the FMS ability to assess movement quality and predict lower body injury risk.

The FMS consists of seven movement patterns (deep squat, hurdle step, in-line lunge, shoulder mobility, active straight leg raise, trunk stability push-up, and quadruped rotary stability) that require neuromuscular motor control revealed through an equilibrium of mobility and stability (Cook et al., 2014a). Three clearing tests (shoulder impingement, spinal extension, and spinal flexion) are incorporated to assess the presence of pain that might have been hidden during the test (Cook et al., 2014a, 2014b). Each movement is scored based on the ability to perform the movement pattern with or without pain or compensation using a four point ordinary scale: zero representing pain and three expressing lack of compensation through the movement pattern. The score of two is representative of compensatory movement that enables the participant to perform the movement. On the other hand, a score of one represents the inability of performing the movement despite the usage of compensatory movements in the absence of pain. Table 1 presents the description of each test as well as clearing tests and land markers. Table 2 presents the specific guidelines to score each test.

Table 1 FMS Testing Description

| Test | Landmarkers measurements and Clearing test | | Starting position | Movement |
|---|---|---|---|---|
| Deep squat | | | Feet shoulder width aligned in the sagital plane. Dowel pressed derectly overhead with shoulders flexed and abducted, elbows extended | Descend as far as possible into a squat position while maintaining an upright torso, keeping the heels and the dowel in position. |
| Hurdle step | Tibial tuberosity height ( from the floor to the tibial tuberosity) | | Hurdle adjusted to individual's tibial tuberosity height. Feet together and toes touching the board. Dowel placed behind the neck, across both shoulders, and held with both hands. | Maintain upright posture and step over the hurdle, raising the foot towards the shin, and maintaining alignment between the foot, knee, and hip, and touch their heel to the floor (without accepting weight) while maintaining the stance leg in an extended position. The moving leg is then returned to the starting position. |
| Inline lunge | Tibial tuberosity height ( from the floor to the tibial tuberosity) | | Standing on the board, both toes must point forward and feet must beging flat. The distance between both feet is equal to the tibial tuberosity height. The dowel is place vertically behind the back touching the head, thoracic spine, and middle of the buttocks. The hand opposit to the front foot holds the dowel at the cervical spine while to other hand holds it at the lumbar spine. | Lower the back knee enough to touch the surface behind the heel of the front foot, while maintaining an upright posture, and then return to the starting position. |
| Shoulder mobility | Hand length: distance from the distal wrist crease to the tip of the third digit in inches | Shoulder impingement: hand is place on the opposite shouler and elbow is raise towards forehead. If pain is noted, zero is awared. | A "T" position is assumed with both arms extended and shoulders abducted. Each hand should be making a fits with thumbs inside. | Reach both fists as close as possible behind the back. The bottom arm will then assume a maximally adducted, extended, and internally rotated position on the shoulder. The top arm will then assume a maximally abducted, flexed, and externally rotated position on the shoulder. |
| Active straight-leg raise | Mid-point between anterior superior iliac spine and patella. | | Lying supine with arms in anatomical position, place the legs over the 2 x 6 board and keep head flat on the ground. During the test the opposite knee (the down leg) must remain in contact with the ground and the toes pointed upward, and the head in contact with the floor. The dowel is held by tester vertically at the midpoint identified with the landmark. | Lift the test leg with a dorsifl exed ankle and an extended knee untill the end range position is achieved. |
| Trunk stability pushup | Spinal extension: from a push up position, press the shoulders up while keeping the hips in contact with the floor. If pain is noted, zero is awared. | | Prone position with feet together. The hands are placed shoulder width apart at the appropriate position according to the described criteria. | Perform a pushup from this position. |
| Rotatory stability | Spinal flexion: from a quadruped position, rock back and touch the buttocks to the heels and the chest to the thighs. If pain is noted, zero is awared. | | Quadruped position (shoulders and hips at 90-degree angle) with the 2 x 6 borad placed between hands and knees. | Simultaneously, flexe the shoulder and extend the same side hip and knee enough to clear approximatly 6 inches from the floor. Then the same limbs are extended and flexed, respectively for the elbow and knee to touch. |

Adapted from Cook et al. 2014a, 2014b.

Table 2 FMS Scoring Criteria

| Test | Scoring criteria | | | |
|---|---|---|---|---|
| | 3 | 2 | 1 | 0 |
| Deep squat | Upper torso is parallel with tibia or toward vertical | Upper torso is parallel with tibia or toward vertical | Tibia and upper torso are not parallel | Pain |
| | Femur below horizontal | Femur below horizontal | Femur is not below horizontal | |
| | Knees are aligned over feet | Knees are aligned over feet | Knees are not aligned over feet | |
| | Dowel aligned over feet | Dowel aligned over feet | Lumbar flexion is noted | |
| | | Heels are elevated | | |
| Hurdle step | Hips, knees and ankles remain aligned in the sagittal plane | Alignment is lost between hips, knees and ankles | Contact between foot and hurdle occurs | Pain |
| | Minimal to no movement is noted in lumbar spine | Movement is noted in lumbar spine | Loss of balance is noted | |
| | Dowel and hurdle remain parallel | Dowel and hurdle do not remain parallel | | |
| Inline lunge | Dowel contacts maintained | Dowel contacts not maintained | Loss of balance is noted | Pain |
| | Dowel remains vertical | Dowel does not remain vertical | | |
| | No torso movement noted | Movement noted in torso | | |
| | Dowel and feet remain in sagittal plane | Dowel and feet do not remain in sagittal plane | | |
| | Knee touches board behind heel of front foot | Knee does not touch behind heel of front foot | | |
| Shoulder mobility | Fists are within one hand length | Fists are within one-and-a-half hand lengths | Fists are not within one and half hand lengths | Pain |
| Active straight-leg raise | Vertical line of the malleolus resides between mid-thigh and ASIS | Vertical line of the malleolus resides between mid-thigh and joint line | Vertical line of the malleolus resides below joint line | Pain |
| | The non-moving limb remains in neutral position | The non-moving limb remains in neutral position | The non-moving limb remains in neutral position | |
| Trunk stability pushup | The body lifts as a unit with no lag in the spine | The body lifts as a unit with no lag in the spine | Men are unable to perform a repetition with hands aligned with the chin | Pain |
| | Men: thumbs aligned with the top of the head | Men: thumbs aligned with the chin | | |
| | Women: thumbs aligned with the chin | Women: thumbs aligned with the clavicle | Women unable with thumbs aligned with the clavicle | |
| Rotatory stability | Performs a correct unilateral repetition | Performs a correct diagonal repetition | Inability to perform a diagonal repetition | Pain |

Adapted from Cook et al. 2014a, 2014b.

The sum of all seven tests scores creates a composite score (FMS score) that ranges from zero to 21. A FMS score of 14 or lower is often interpreted as an indication of higher risk for lower body injury (Chimera et al., 2015; Teyhen et al., 2012). The FMS score has been shown to have a good to moderate interrater and intra-rater reliability indicated by 0.74-0.76 with 95% CIs (Teyhen et al., 2012). Chorba et al. (2010) reported a significant correlation between low-scoring female athletes and injury ($p = 0.021$, $r = 0.76$). Therefore, FMS is a valid tool to assess injury risk among female athletes.

*Knee outcome survey – activity of daily life (KOS-ADL)*

Patient-report measurement of knee function questionnaires are designed to be answered by the patient independently. They are important to assess pain experienced through a variety of activities. There are multiple self-reported questionnaires assessing knee functionality, a couple of them being the Lysholm Knee Scale and the Knee Outcome Survey Activities of Daily Living Scale (KOS-ADL). Lysholm Knee Scale is a well-established scale often used with patients following knee ligament surgery (Collins, Misra, Felson, Crossley, & Roos, 2011; Irrgang et al., 1998; Marx et al., 2005). However, its validity among the athletic population might be limited. The KOS-ADL is focused on assessing knee functionality of a variety of knee disorders among the athletic population (Collins et al., 2011; Marx et al., 2005). Irrgang et al. (1998) reported KOS-ADL test-retest reliability coefficient to be 0.97 and compared KOS-ADL to the Lysholm Knee Scale, finding a moderately strong correlation ($r = 0.78$ to $0.86$). The conclusion drawn by Irrgang et al. (1998) indicates that KOS-ADL can be safely used to assess functional limitations on athletes suffering from a wide variety of knee disorders.

## Chapter 3: Methods

### Participants

The subject population consisted of sixteen (n = 16) female members of a collegiate synchronized swimming team (mean +/- S.D. = Age: 20.5 +/- 1.8y, Height: 165.8 +/- 5.1cm, Weight: 63.8 +/- 5.8kg). Participants have approximately 13.1 +/- 2.4y of synchronized swimming experience. The participants typically trained 17.3 +/- 3.0h.wk$^{-1}$ with training consisting of 2.3 +/- 0.9h.wk$^{-1}$ of land-based training, 10.7 +/- 3.6h.wk$^{-1}$ of water-based training and 3.3 +/- 0.6h.wk$^{-1}$ of sport specific strength and conditioning training. Any individual who reported as being under the care of a physician or had previously been diagnosed with cardiac, pulmonary, metabolic, renal, hepatic, musculoskeletal, or psychiatric conditions that would have interfered with physical activity was excluded from the study. Prior to participating in the investigation, participants were informed of all potential risks and procedures involved with the study. This study was approved by the Institutional Review Board (IRB) through Lindenwood University (1/12/17, study # 1006575-1). This study focused on using non-probability convenience sampling of current collegiate synchronized swimmers.

### Procedures

On the testing date, each participant performed the following assessments: postural analysis, hip mobility, movement quality, hip strength, and a pain questionnaire. To maintain test reliability, the same evaluator performed each assessment. Anthropometric measurements (age, height, and weight) were also collected on the testing date.

A certified athletic trainer (AT) analyzed each participant's posture hip mobility using a goniometer. For the postural analysis, as described by Woodland & Francis (1992), the participant lied supine on the table while the AT measured the Q-angle using a goniometer. The fulcrum of the goniometer was placed at the center of the patella, the inferior arm was lined up with the tibia tuberosity, and the superior arm lined up with the anterior superior iliac spine (ASIS). For hip mobility [internal (IR) and external (ER) rotation], the participant lied prone on the table with knees flexed at 90° with the femur of the evaluated leg parallel to the floor as described by Simoneau et al. (1998). The AT then aligned the fulcrum of the goniometer with the center of the patella keeping the stationary arm perpendicular to the floor, and the movable arm aligned with the anterior midline of the leg or the crest of the tibia (Simoneau et al., 1998). Each movement (IR or ER) was performed three times and the highest value was recorded to the nearest degree, as suggested by Simoneau et al. (1998).

Seven FMS-trained professionals assessed the movement quality. As previously described, the FMS is based on seven movements graded according to the participant's ability to execute each movement (Cook et al., 2014). A single professional evaluated each movement in order to maintain test reliability. The participants who volunteered for the study lined up in an assembly line matter rotating though each evaluator. FMS clearance test and bone mark measurements previously described were performed following each test as suggested by Cook et al. (2014).

Hip strength tests were performed using an external force transducer. Hip abduction (ABD) and adduction (ADD) isometric maximal strength was measured with the participant lying on their side on a table (Ireland et al., 2003). The table utilized for this study contained an opening on one of its ends, enabling a better line of pull for the force transducer attachment. In order to ensure proper placing of the top leg during ABD, a foam roll was placed to support the top leg at 10° hip abduction and 10° hip extension measured in relation to the ASIS (Ireland et al., 2003). The force transducer was fixed to a steel plate on the ground underneath the table and to a thigh strap, which was wrapped around the participants' knee 1cm above the knee joint, as described by Ireland et al. (2003). Participants were then oriented to exert maximal force through their hip abductors while attempting to lift their leg into the air. For ADD, the participant stayed lying on her side with the top leg rested on the foam roll such that hips and knee were at 90° of flexion. The bottom leg was then attached to the force transducer through the thigh straps, which were placed 1cm above the knee joint as described above.

Hip IR and ER strength were also tested using the force transducer. However, this time the force transducer was fixed perpendicular to the floor such as the pulling vector was parallel to the floor. The participant sat on a 90cm box with hips and knees flexed at 90° (Ireland et al., 2003). In order to prevent the participant utilizing hip abductors or adductors instead of hip external or internal rotators respectively, a foam roll was placed between the participant's thighs during IR and ER tests. An ankle strap was placed proximally to the medial malleolus (Ireland et al., 2003) and attached to the force transducer.

During each isometric test, the participant was instructed to apply maximal force for 5sec and rest for 15sec between trials (Bolgla et al., 2008; Ireland et al., 2003; Kollock et al., 2015; Sled, 2008). One familiarization trial followed by three recorded trials were executed in each test, with the peak-computed value recorded for data analysis purpose (Bolgla et al., 2008; Ireland et al., 2003;).

Finally, each participant received a paper questionnaire, the KOS-ADL, designed by Irrgang et al. (1998) to evaluate the functional limitations during activities of daily living caused by disorders and pathologies of the knee. The KOS-ADL has previously been evaluated for validity and reliability (Marx et al., 2005; Collins et al., 2011). Participants were instructed to individually answer each question in reference to the last one to two days to the best of their abilities. An evaluator was available to further assist participants who had questions.

Finally, at the end of the season, athletes completed a simple questionnaire. This follow up questionnaire enquired about the situation and the characteristics of the pain, if experienced at some point. Furthermore, participants also reported the knee affected and the length of the occurrence.

**Analysis Procedures**

Any participant who did not complete the initial strength tests was excluded from the analysis. This study investigated the correlation among knee pain and hip strength, hip mobility, movement quality, and Q-angle. Secondly, this study investigated the association of knee pain occurrence throughout season, during exercise, or during activities of daily living and hip strength, hip mobility, movement quality, and Q-angle. Finally, the present study identified the current strength and mobility profile of collegiate synchronized swimmers. Descriptive statistics were performed for every variable. Pearson Correlations and Independent T-tests were utilized to identify significance, which was set at $p<0.05$.

## Chapter 4: Results

The purpose of this study was to identify factors related to knee pain in collegiate synchronized swimmers. It was hypothesized that knee pain would be correlated with hip musculature strength, hip mobility, movement quality, and Q-angle (hypothesis one). A secondary hypothesis stated that the presence of knee pain expressed through three different situations [one general – in season (S), and two specific – during exercise (EX) or during activities of daily living (ADL)] is associated with hip strength, hip mobility, movement quality, and Q-angle (hypothesis two). In addition, the present study also aimed to investigate the current strength and mobility profile of collegiate synchronized swimmers (hypothesis three).

*Hypothesis one*

Analysis of knee pain assessed through KOS-ADL showed no correlation with any other measured variables (hip strength, hip mobility, movement quality, and Q-angle). A moderate correlation with hip adductor strength was observed to be almost significant ($r = 0.488$, $p = 0.055$). Table 5 with all correlations is available in the appendix C.

*Hypothesis two*

Three separate Independent T-tests were used to analyze the difference of each measured variable among athletes who did or did not experienced knee pain in three different situations (S, ADL, EX) Table 6 with all significant differently means resulted from t-test is available on appendix C. Those who experienced pain at some point during the season (season pain (SP) n = 12, season no pain, (SNP) n = 4) expressed better movement quality assessed through FMS ($FMS_{SP} = 16 > FMS_{SNP} = 13.25$, $p = 0.014$). No other variable showed to be significantly different between the two S groups.

When comparing EX groups (exercise pain (EXP) n = 7; exercise no pain (EXNP) n = 9), those who experienced pain possessed greater hip mobility and weaker hip musculature. Hip external rotation mobility of the right leg was about 13° greater on EXP group ($mER^{R}_{EXP} = 43$ °, $mER^{R}_{EXNP} = 30°$, $p = 0.017$). Hip strength particularly of the left leg was significantly lower in the pain group for external rotation as well as for adduction ($sER^{L}_{EXP} = 79N$, $sER^{L}_{EXNP} = 94N$, $p = 0.044$; $sADD^{L}_{EXP} = 124N$, $sADD^{L}_{EXNP} = 191N$, $p = 0.019$).

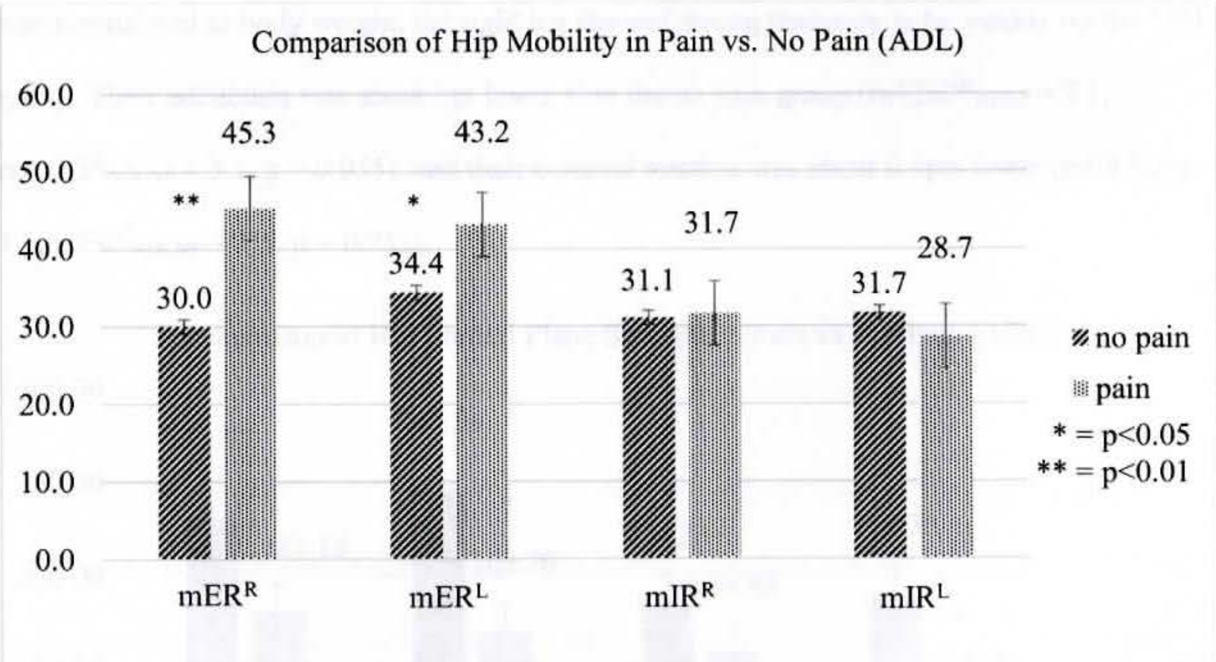


Figure 1 Mean Hip Mobility between pain and no pain during Activities of Daily Living

When variables were analyzed according to pain experienced during activities of daily living (activities of daily living pain (ADLP) n = 6; activities of daily living no pain (ADLNP) n = 10), mobility was greater and strength lower on those who experienced pain (Figure 1). Hip external mobility of both legs was greater in the pain group compared to the no pain group during activities of daily living ($mER^{R}_{ADLP} = 45°$, $mER^{R}_{ADLNP} = 30°$, $p = 0.005$; $mER^{L}_{ADLP} = 43°$, $mER^{L}_{ADLNP} = 34°$, $p = 0.055$). Moreover, the total range of motion of the right leg was approximately 16° greater on the pain group ($mSUM^{R}_{ADLP} = 77°$, $mSUM^{R}_{ADLNP} = 61°$, p =

0.029). On the other hand, those who experienced pain during activities of daily living had weaker hip musculature especially in their left leg (Figures 2 and 3). Their internal rotation strength was approximately 57N weaker ($sIR^{L}_{ADLP}$ = 71.22N, $sIR^{L}_{ADLNP}$ = 128.29N, $p = 0.003$). In addition, those who experienced pain during activities of daily living were about 76N weaker on left hip abduction ($sABD^{L}_{ADLP}$ = 169.69N, $sABD^{L}_{ADLNP}$ = 245.54N, $p = 0.040$) and 72N on left hip adduction ($sADD^{L}_{ADLP}$ = 117.12N, $sADD^{L}_{ADLNP}$ = 189.34N, $p = 0.013$). When strength was normalized to body weight, the right leg showed strong tendency to be weaker on the ADLP group. Their adduction was about 1pt lower than the no pain group ($rsADD^{R}_{ADLP}$ = 2.1, $rsADD^{R}_{ADLNP}$ = 3.1, $p = 0.055$), and their external rotation was about 0.4pts lower ($rsER^{R}_{ADLP}$ = 1.1, $rsER^{R}_{ADLNP}$ = 1.5, $p = 0.052$).

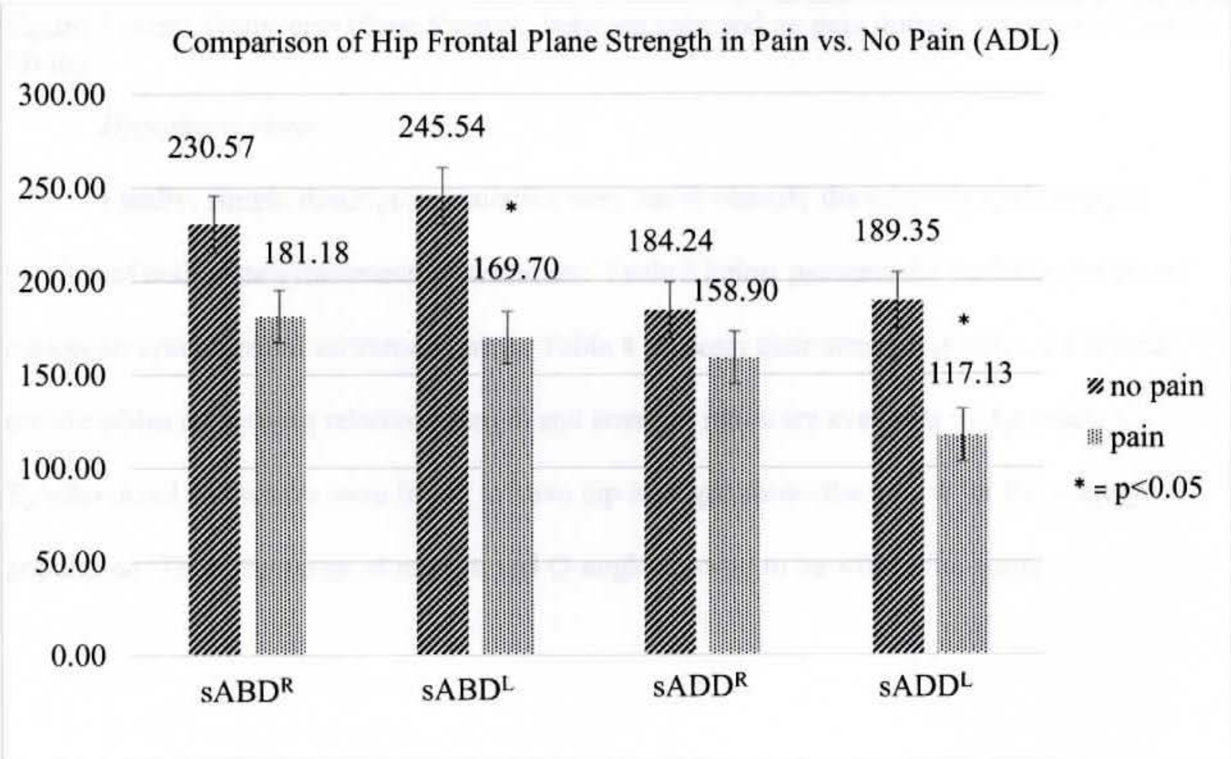


Figure 2 Mean Frontal Plane Strength between pain and no pain during Activities of Daily Living

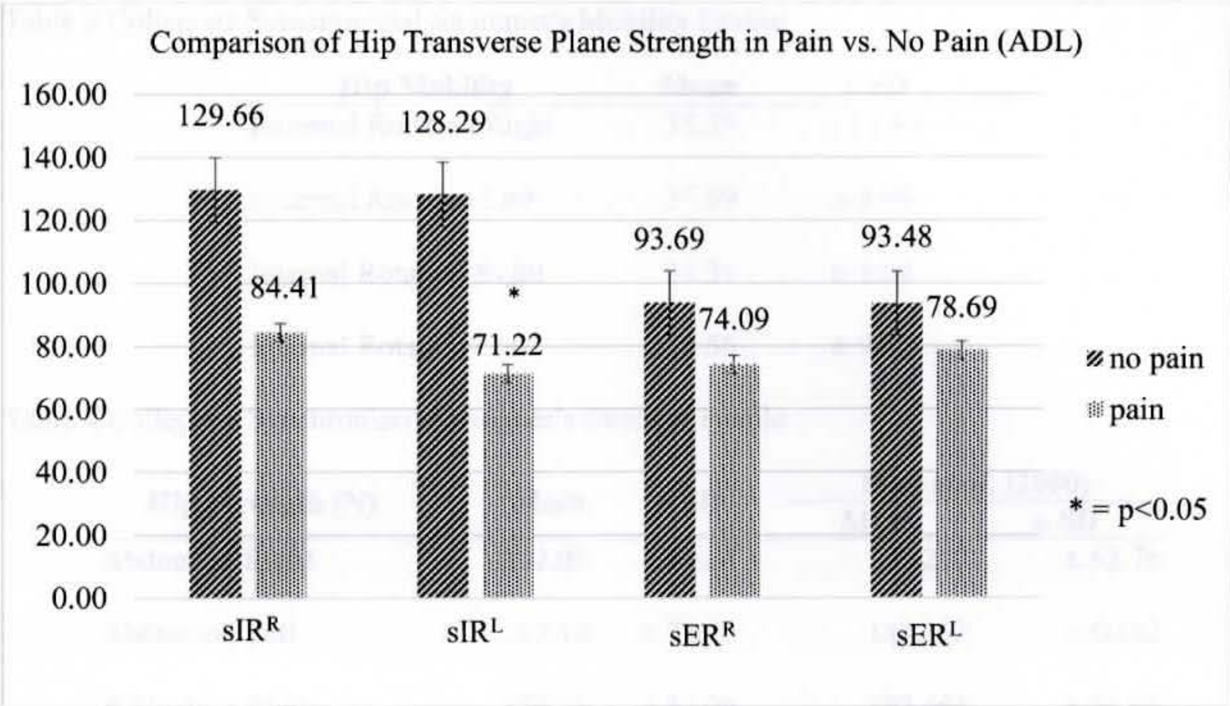


Figure 3 Mean Transverse Plane Strength between pain and no pain during Activities of Daily Living

*Hypothesis three*

Finally, simple descriptive statistics were ran to identify the mobility and strength profiles of collegiate synchronized swimmers. Table 3 below presents the mobility profile of collegiate synchronized swimmers, while Table 4 presents their strength profile. Additional profile tables addressing relative strength and strength ratios are available in Appendix C. Synchronized swimmers were found to have hip strength above the norms for the average population. Their hip range of motion and Q-angle showed to be within the norm.

Table 3 Collegiate Synchronized Swimmer's Mobility Profile

| Hip Mobility | Mean | ± SD |
|---|---|---|
| External Rotation Right | 35.75 | ± 11.48 |
| External Rotation Left | 37.69 | ± 8.99 |
| Internal Rotation Right | 31.31 | ± 9.07 |
| Internal Rotation Left | 30.56 | ± 9.36 |

Table 4 Collegiate Synchronized Swimmer's Strength Profile

| Hip Strength (N) | Mean | ± SD | Stoll et al. (2000) | |
|---|---|---|---|---|
| | | | Mean | ± SD |
| Abduction Right | 212.05 | ± 64.64 | 193.257 | ± 63.76 |
| Abduction Left | 217.10 | ± 73.29 | 188.352 | ± 60.82 |
| Adduction Right | 174.74 | ± 53.06 | 182.466 | ± 54.93 |
| Adduction Left | 162.26 | ± 59.44 | 181.485 | ± 52.97 |
| Internal Rotation Right | 112.69 | ± 51.59 | 77.499 | ± 23.54 |
| Internal Rotation Left | 106.89 | ± 44.18 | 76.518 | ± 24.52 |
| External Rotation Right | 86.34 | ± 23.94 | 83.385 | ± 22.56 |
| External Rotation Left | 87.93 | ± 25.84 | 80.442 | ± 22.56 |

Graphic Legend

| Legend | | Legend | |
|---|---|---|---|
| sADD$^{R}$ | strength adduction right | mER$^{R}$ | mobility external rotation right |
| sADD$^{L}$ | strength adduction rotation left | mER$^{L}$ | mobility external rotation left |
| sABD$^{R}$ | strength abduction right | mIR$^{R}$ | mobility internal rotation right |
| sABD$^{L}$ | strength abduction rotation left | mIR$^{L}$ | mobility internal rotation left |
| sER$^{R}$ | strength external rotation right | | |
| sER$^{L}$ | strength external rotation left | | |
| sIR$^{R}$ | strength internal rotation right | | |
| sIR$^{L}$ | strength internal rotation left | | |

## Chapter 5: Discussion

The present research studied synchronized swimmers, a population on which limited research is available. Mountjoy (1999 & 2009) documented anecdotal observations regarding sports demands and common injuries. Chu et al. (2009) focused on injuries experienced by synchronized swimmers. Later authors devoted their efforts on performance aspects of the sport (Rodríguez-Zamora et al., 2012; Schaal et al., 2013; Robertson et al., 2014). Rodríguez-Zamora et al. (2012) studied the physiological responses during competition. Schaal et al. (2013) analyzed the effect of different acute recovery techniques on synchronized swimmers. Overall, scientific information on synchronized swimming is limited. When available, the information is regarding elite world-class athletes. The present study proposed to investigate the characteristics of collegiate synchronized swimmers.

The primary finding of the present study indicated a link between poor hip strength and an increased risk of knee pain among collegiate synchronized swimmers. Our results also highlighted that synchronized swimming potentially induces unique physical demands in regards to strength and mobility. Finally, the present study was able to identify the current strength and mobility profile of collegiate synchronized swimmers.

According to Cant et al. (2014), patellofemoral stress is increased with the lack of hip musculature control. One in four active adults suffers of patellofemoral pain syndrome (Boling et al., 2009). The female population seems to have an even greater tendency of experiencing this knee discomfort. Both Chu (1999) and Mountjoy (1999 & 2009) have documented that knee injury is frequently observed among synchronized swimmers. The present study observed that those athletes who experienced knee pain, during EX or ADL, had consistently lower levels of hip strength as shown on Figures 2 and 3. Lower levels of strength often leads to decreased movement control. Souza & Powers (2009) hypothesized that the lack of hip muscular control may allow excessive hip motion in the frontal and transverse planes. This excessive transverse and frontal plane motion might result in increased dynamic Q-angle during a variety of movements including the eggbeater. Even though the present study reported a normal Q-angle (normal: <19°, observer: 16°), the observed lower hip strength among collegiate synchronized swimmers who experienced knee pain might allow the knee to be exposed to dynamic positions that places greater stress on the patellofemoral joint. Synchronized swimmers who have poor hip musculature strength might experience greater valgus load not only during the eggbeater kick, but also during ADL as well as other training-related activities.

Page et al. (2010), Bolgla et al. (2008), and Hott et al. (2015) identified that lower strength in particular of the hip abductors and the external rotators could lead to patellofemoral malalignment, resulting in greater knee pain. In the present study, data from the ADL group indicated a significant difference between the strength levels of the abductors, especially of the left side ($sABD^{L}_{ADLP} = 169.69N$, $sABD^{L}_{ADLNP} = 245.54N$, $p = 0.040$), despite the fact that synchronized swimming is a symmetric sport (more will be discussed regarding symmetry). Our findings support the hypothesis linking lack of hip abductor strength and knee pain. Hip abductor muscles assist the patella to remain in congruence with the femoral grove. Weakness in such musculature might cause excessive hip adduction allowing the knee to drop inward into a valgus position. Cant et al. (2014) defends that excessive hip adduction and internal rotation contributes to patellofemoral joint stress. Therefore, strengthening exercises are advised to offset hip musculature imbalances

The lack of strong correlations between knee pain and other variables. The lack of strong correlations between knee pain and other variables could have been influenced by the relatively small roster of collegiate synchronize swimming teams. However, a weak correlation was found with hip adductor musculature ($r = 0.488$, $p=0.055$). This would suggest that weaker hip adductors could be linked with knee pain reported as lower KOS-ADL scores. Even though the literature proposes the existence of a link between hip abduction weakness and PFPS, the present study findings suggests that the existence of another factor associating knee pain to hip adduction strength. However, a larger sample size is needed to allow better correlations to be observed and future studies might strive to recruit more than one team.

Synchronized swimming is a sport that values flexibility for its acrobatic movements. The hypothesis linking knee pain and relative joint position suggests that excessive hip internal rotation could be linked with knee pain (Bolgla et al., 2008; Hott et al, 2015). The present study found that those who experienced knee pain during EX or ADL also presented larger range of motion, with greater significance in the right leg (mean difference: $mER^{R}_{ADL} = 15.33°$, $p = 0.005$; $mER^{R}_{EX} = 13.14°$, $p = 0.017$; $mER^{L}_{ADL} = 8.77°$, $p = 0.055$). While limb imbalances will be discussed next, the findings of the present study seem to not match the hypothesis suggested by other authors, since similar internal rotation mobility was observed regardless of the presence of knee pain. On the other hand, when analyzing the total arch of motion in the transverse plane, the pain group tended to have greater mobility (mean difference: $mSUM^{R}_{ADL} = 15.9°$, $p = 0.029$). These findings suggest that the ability to move uninhibited through a greater range of movement around the hip joint might lead to greater knee joint instability. Professionals working with sports that value flexibility, such as synchronized swimming, should be conscious of the consequences of greater mobility on joint stability, especially when lack of strength is also present.

The findings of the present study showed an interesting trend: those who experienced knee pain either during EX or ADL also presented significantly lower levels of left leg strength, while the right leg was significantly more mobile. Additional correlation test was used to identify any association of limb asymmetry assessed through FMS and knee pain. Despite the fact that nine athletes were identified with some type of asymmetry, no correlation with knee pain was observed. Synchronized swimming is a symmetric sport; the eggbeater requires both legs to be kicking concomitantly in order to maintain the ability to tread water (Homma & Homma, 2005). Oliveira et al. (2016) suggests that the eggbeater kick might be linked to multiple conditions of the knees such as patellofemoral syndrome, chronic overuse injury in the knee, adductor-muscle strains, and tenosynovitis of the extensor longus tendon. However, the trend found by the present study indicates the influence of other factors on mobility and strength profile. The eggbeater kick is a symmetric movement; however, it was observed that the right leg presented greater mobility, while the left leg lacked strength. This imbalance might be a consequence of postural or other developmental asymmetry.

According to Cook et al. (2014), a perfect FMS score of a single test is a three, which represents the ability to show muscular coordination through the entire range of motion. After completing all seven tests, a maximum of 21 points is available. The present study showed that those who experienced pain at some point throughout the season tended to accumulate higher scores on the FMS screen (2.75 points greater, $p = 0.014$). Although the FMS was chosen as an indicator of movement quality, a perfect score might favor those with greater range of motion. This finding brings to discussion the need to pursue a three on individual FMS tests. Our results suggest that a perfect score for this type of athlete might not be ideal or even lead to greater likelihood of knee pain.

Mountjoy (2009) described elite synchronized swimmers typically spending about $40h.wk^{-1}$ training, from which 20 to $32h.wk^{-1}$are spent in the pool (8-10 times a week, 2-4hrs per session). The remaining hours are devoted to cross training on land, emphasizing fitness development (Mountjoy, 2009). The collegiate synchronized swimmer is limited by collegiate regulation on the total training hours. The NCAA limits all to a maximum of 20hrs per week of athletic-related activities (NCAA, n.d.). According to the present study's findings, the collegiate athlete spends on average $17h.wk^{-1}$ training, which includes about $10h.wk^{-1}$ in the pool, 1.5 to $3.5h.wk^{-1}$ land drilling, and $3h.wk^{-1}$ of strength and conditioning. Although collegiate regulation limits the training load, it seems that the training distribution is similar between elite and collegiate athletes. Mountjoy (2009) describes any extra pool training as cross training while the present study separately analyze land drill and strength and conditioning training. Table 9 on appendix C summarizes the comparison of the anecdotal observations from Mountjoy (2009) and the finding from the present study.

In addition, the present study identified the strength and mobility profile of collegiate synchronized swimmers (Tables 3, 4, 6, and 7). In general, collegiate synchronized swimmers present hip mobility and Q-angle values within norms. They are often stronger than the average population in respect to frontal and transverse plane motions at the hip joint. However, though greater than the average population, their strength levels might not be adequate to sustain the stressors placed by the sport.

The simple correlation statistical test showed that no variable was associated with knee pain. However, when the data was separated into groups according to when knee pain was experienced, interesting associations were found. An increased mobility was observed on those who experienced knee pain (Figure 1). Lower levels of hip musculature strength appeared more often on that same group (Figure 2 and 3). The present study reported that collegiate synchronized swimmers have within norms Q-angle and mobility, as well as generally stronger hip musculature than the average population (Table 4). Yet, the demands of the sport might require greater levels of strength while favoring less hypermobile athletes. This hypothesis is supported by the fact that those who experienced knee pain consistently expressed lower hip strength.

**Practical application**

Despite the open kinetic chain nature of the sport, these athletes often train on land as well. It is important that professionals working with synchronized swimmers are aware of the valgus load during variety of land and water based movements. The lack of hip musculature strength observed by the present study might lead to increased knee joint stress. Activities such as running, squatting, and jumping might allow greater valgus load in the absence of hip control.

Knee pain is a multifactorial, self-reported condition that often is a precursor for several diagnosed injuries such as patellofemoral pain syndrome. The professional working with synchronized swimming should be aware of the prevalence of knee pain or discomfort among athletes in this sport. The synchronized swimmer might benefit from hip musculature strengthening routines focused especially on abductors and external rotators. Such routines should stimulate the gluteus medius, the tensor fascia lata, the upper fibers of the gluteus maximus, the quadratus femoris, the pectineus, the biceps femoris, and the iliopsoas muscles, since those muscles aid in abduction and external rotation of the hips. Stastny et al. (2016) highlights the muscle activation during a variety of lower body exercises. A professional deriving a strength program aiming to decrease muscle imbalance could refer to Stastny et al. (2016) study for proper exercises selection.

**Future Research**

Suggestions for future research have arisen from investigations. Future studies should strive for larger sample size and recruit more than one synchronized swimming team. Although the bilateral nature of the sport, other factors such as leg dominance or postural asymmetry might influence the development of unilateral discomfort. Therefore, future studies could enquire leg limb dominance when investigating knee pain. The Postural Restoration Institute – PRI explores postural asymmetries (Boyle, n.d.). Future studies might investigate the influence of postural asymmetry on symmetric sports. Additionally, though flexibility is valued in the sport, the relation of hypermobility and injury risk should be further investigated. The Beighton Score seems to be an interesting hypermobility test that can guide future studies (Hakim, 2012).

**Conclusion**

In conclusion, synchronized swimming seems to demand above average hip musculature strength while favoring non hypermobile athletes. Knee pain is a multifactorial condition prevalent among synchronized swimmers. The implementation of hip strengthening routines focusing on abductor and external rotator muscle groups is advised to aid prevention of knee pain. Additionally, perfect FMS might not be ideal for this population and hypermobility might be a concern.

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## Appendix A: Pre Season Questionnaire

## *Training History Questionnaire*

*Please read carefully each question and answer each to the best of your ability.*

1. Date of birth (mm/dd/yy) ____/______/_____

2. Approximately, how many years have you been training with Synchronized Swimming?____

3. How long have you been training with the Lindenwood Synchronized Swimming team?____

4. On average, how many hours per week do you spend involved with synchro?____________

5. What is a common break down for each activity during a typical week?

- Pool training: ________ hours/week
- Land drill: ________ hours/week
- Strength & conditioning: _____ hours/week
- Others (please specify): ______ hours/week

6. Have you ever experienced a sport-related injury that limited your participation in the sport?

**YES** **NO**

   - If yes, how many injuries were there and approximately how long did each injury last?

________________________________________________________________

________________________________________________________________

________________________________________________________________

# Knee Outcome Survey
# Activities of Daily Living Scale

***INSTRUCTIONS:***
***Please mark ONLY the response that best describes the symptoms and limitations that you have experienced because of your knee while performing each of these usual daily activities over the last 1 to 2 days.***

| To what degree do the following affect your daily activity level? (Please fill in ONLY ONE BUBBLE PER ROW.) | Never have it | Have it, but it does not affect my daily activity | It affects my activity slightly | It affects my activity moderately | It affects my activity severely | It prevents me from performing all daily activities |
|---|---|---|---|---|---|---|
| 1. Pain in your knee | O | O | O | O | O | O |
| 2. Grinding or grating of your knee | O | O | O | O | O | O |
| 3. Stiffness in your knee | O | O | O | O | O | O |
| 4. Swelling in your knee | O | O | O | O | O | O |
| 5. Slipping of your knee | O | O | O | O | O | O |
| 6. Buckling of your knee | O | O | O | O | O | O |
| 7. Weakness or lack of strength of your leg | O | O | O | O | O | O |

**Please fill in ONLY ONE BUBBLE for each question.**

**8. How does your knee affect your ability to walk?**

- O My knee does not affect my ability to walk.
- O I have pain in my knee when walking, but it does not affect my ability to walk.
- O My knee prevents me from walking more than 1 mile.
- O My knee prevents me from walking more than $\frac{1}{2}$ mile.
- O My knee prevents me from walking more than 1 block.
- O My knee prevents me from walking.

**9. Because of your knee, do you walk with crutches or a cane?**

- O I can walk without crutches or a cane.
- O My knee causes me to walk with 1 crutch or a cane.
- O My knee causes me to walk with 2 crutches.
- O Because of my knee, I cannot walk even with crutches.

**10. Does your knee cause you to limp when you walk?**

- O I can walk without a limp.
- O Sometimes my knee causes me to walk with a limp.
- O Because of my knee, I cannot walk without a limp.

**Please fill in ONLY ONE BUBBLE for each question.**

**11. How does your knee affect your ability to go UP stairs?**

- ○ My knee does not affect my ability to go up stairs.
- ○ I have pain in my knee when going up stairs, but it does not limit my ability to go up stairs.
- ○ I am able to go up stairs normally, but I need to rely on use of a railing.
- ○ I am able to go up stairs one step at a time with use of a railing.
- ○ I have to use crutches or a cane to go up stairs.
- ○ I cannot go up stairs.

**12. How does your knee affect your ability to go DOWN stairs?**

- ○ My knee does not affect my ability to go down stairs.
- ○ I have pain in my knee when going down stairs, but it does not limit my ability to go down stairs.
- ○ I am able to go down stairs normally, but I need to rely on use of a railing.
- ○ I am able to go down stairs one step at a time with use of a railing.
- ○ I have to use crutches or a cane to go down stairs.
- ○ I cannot go down stairs.

**13. How does your knee affect your ability to stand?**

- ○ My knee does not affect my ability to stand. I can stand for unlimited amounts of time.
- ○ I have pain in my knee when standing, but it does not limit my ability to stand.
- ○ Because of my knee, I cannot stand for more than 1 hour.
- ○ Because of my knee, I cannot stand for more than $\frac{1}{2}$ hour.
- ○ Because of my knee, I cannot stand for more than 10 minutes.
- ○ I cannot stand because of my knee.

**14. How does your knee affect your ability to kneel on the front of your knee?**

- ○ My knee does not affect my ability to kneel on the front of my knee. I can kneel for unlimited amounts of time.
- ○ I have pain when kneeling on the front of my knee, but it does not limit my ability to kneel.
- ○ I cannot kneel on the front of my knee for more than 1 hour.
- ○ I cannot kneel on the front of my knee for more than $\frac{1}{2}$ hour.
- ○ I cannot kneel on the front of my knee for more than 10 minutes.
- ○ I cannot kneel on the front of my knee.

**15. How does your knee affect your ability to squat?**

- ○ My knee does not affect my ability to squat. I can squat all the way down.
- ○ I have pain when squatting, but I can still squat all the way down.
- ○ I cannot squat more than $\frac{3}{4}$ of the way down.
- ○ I cannot squat more than $\frac{1}{2}$ of the way down.
- ○ I cannot squat more than $\frac{1}{4}$ of the way down.
- ○ I cannot squat at all.

**16. How does your knee affect your ability to sit with your knee bent?**

- ○ My knee does not affect my ability to sit with my knee bent. I can sit for unlimited amounts of time.
- ○ I have pain when sitting with my knee bent, but it does not limit my ability to sit.
- ○ I cannot sit with my knee bent for more than 1 hour.
- ○ I cannot sit with my knee bent for more than $\frac{1}{2}$ hour.
- ○ I cannot sit with my knee bent for more than 10 minutes.
- ○ I cannot sit with my knee bent.

**17. How does your knee affect your ability to rise from a chair?**

- ○ My knee does not affect my ability to rise from a chair.
- ○ I have pain when rising from the seated position, but it does not affect my ability to rise from the seated position.
- ○ Because of my knee, I can only rise from a chair if I use my hands and arms to assist.
- ○ Because of my knee, I cannot rise from a chair.

## Appendix B: Follow up Questionnaire

## *Follow up Questionnaire*

*Please read carefully each question and answer each to the best of your ability.*

1. At any time throughout this season, have you experienced knee pain?

**YES** **NO**

2. In which knee did you experience pain?

**RIGHT** **LEFT** **BOTH**

3. When was knee pain present? Roughly, how long did the pain least?

*(e.g.: about January for around 3-weeks OR since second week of February in left knee)*

________________________________________

________________________________________

________________________________________

4. To what degree does pain in your knee affected your DAILY ACTIVITY level? (things like walking to class, standing, sitting etc)

   - o Never have it
   - o Have it, but it does not affect my daily activity
   - o It affects my activity slightly
   - o It affects my activity moderately
   - o It affects my activity severely
   - o It prevents me from performing all daily activities

5. To what degree does pain in your knee affected your ABILITY TO TRAIN OR EXERCISE?

   - o Never have it
   - o Have it, but it does not affect my training
   - o It affects my training slightly
   - o It affects my training moderately
   - o It affects my training severely
   - o It prevents me from performing all training activities

## Appendix C: Tables

Table 5 Correlation between knee pain (KOS-ADL) and measured variables

| Variable | r-value | p-value |
|---|---|---|
| Movement Quality | | |
| FMS score | -.048 | .859 |
| Q-angle | | |
| Q-angle Right | .071 | .794 |
| Q-angle Left | -.220 | .414 |
| Mobility | | |
| mobility external rotation right | .175 | .516 |
| mobility external rotation left | -.011 | .969 |
| mobility internal rotation right | .164 | .544 |
| mobility internal rotation left | .406 | .119 |
| mobility sum right | .240 | .371 |
| mobility sum left | .338 | .200 |
| Strength | | |
| strength adduction right | .488 | .055 |
| strength adduction rotation left | .156 | .565 |
| strength abduction right | -.112 | .679 |
| strength abduction rotation left | -.055 | .840 |
| strength external rotation right | .023 | .933 |
| strength external rotation left | -.036 | .895 |
| strength internal rotation right | -.155 | .567 |
| strength internal rotation left | -.121 | .654 |
| relative strength adduction right | .180 | .505 |
| relative strength adduction rotation left | .392 | .133 |
| relative strength abduction right | .040 | .882 |
| relative strength abduction rotation left | .344 | .192 |
| relative strength external rotation right | .135 | .617 |
| relative strength external rotation left | .139 | .607 |
| relative strength internal rotation right | .058 | .832 |
| relative strength internal rotation left | .000 | .999 |
| Strength ratio adduction:abduction right | .424 | .101 |
| Strength ratio adduction:abduction left | .411 | .114 |
| Strength ratio internal:external right | -.284 | .286 |
| Strength ratio internal:external left | -.146 | .590 |

Table 6 Mean difference between pain and no pain

| Variable | Mean difference | p-value |
|---|---|---|
| Season | | |
| FMS Score | 2.75 | .014 |
| Exercise | | |
| Mobility External Rotation Right | 13.14 | .017 |
| Strength Adduction Rotation Left | -66.90 | .019 |
| Strength Internal Rotation Left | -43.94 | .044 |
| Activities of Daily Living | | |
| Mobility External Rotation Right | 15.33 | .005 |
| Mobility External Rotation Left | 8.77 | .055 |
| Mobility Sum Right | 15.90 | .029 |
| Strength Abduction Rotation Left | -75.85 | .040 |
| Strength Adduction Rotation Left | -72.22 | .013 |
| Strength Internal Rotation Left | -57.07 | .007 |
| Strength Ratio Internal:External Left | -.44588 | .072 |
| Relative Strength Adduction Right | -.95491 | .055 |
| Relative Strength External Rotation Right | -.33751 | .052 |

Table 7 Collegiate Synchronized Swimmer's Relative Strength Profile and Ratios

| Relative Strength(N/kg) | Mean | ± SD |
|---|---|---|
| Abduction Right | 3.36 | ± 1.11 |
| Abduction Left | 3.43 | ± 1.22 |
| Adduction Right | 2.79 | ± 0.98 |
| Adduction Left | 2.60 | ± 1.11 |
| Internal Rotation Right | 1.79 | ± 0.87 |
| Internal Rotation Left | 1.70 | ± 0.74 |
| External Rotation Right | 1.35 | ± 0.34 |
| External Rotation Left | 1.37 | ± 0.34 |
| Adduction:Abduction Right | 0.91 | ± 0.41 |
| Adduction:Abduction Left | 0.78 | ± 0.23 |
| Internal:External rotation Right | 1.29 | ± 0.46 |
| Internal:External Left | 1.25 | ± 0.48 |

Table 8 Collegiate vs Elite Synchronized Swimming Training Load

| | **Mean** | **± SD** | **Mountjoy (2009)** |
|---|---|---|---|
| Training load | 17.3 | ± 3.0 $h.wk^{-1}$ | 40 $h.wk^{-1}$ |
| Pool training | 10.7 | ± 3.6 $h.wk^{-1}$ | 8-10 x 2-4hrs |
| Land base training | 2.3 | ± 0.9 $h.wk^{-1}$ | 4-6 x 45-90min |
| Strength and Conditioning | 3.3 | ± 0.6 $h.wk^{-1}$ | |

Table 9 Variable's Abbreviation

| Abbreviation | Graphic Legend |
|---|---|
| $mER^R$ | mobility external rotation right |
| $mER^L$ | mobility external rotation left |
| $mIR^R$ | mobility internal rotation right |
| $mIR^L$ | mobility internal rotation left |
| $sADD^R$ | strength adduction right |
| $sADD^L$ | strength adduction rotation left |
| $sABD^R$ | strength abduction right |
| $sABD^L$ | strength abduction rotation left |
| $sER^R$ | strength external rotation right |
| $sER^L$ | strength external rotation left |
| $sIR^R$ | strength internal rotation right |
| $sIR^L$ | strength internal rotation left |
| $rsADD^R$ | relative strength adduction right |
| $rsADD^L$ | relative strength adduction rotation left |
| $rsABD^R$ | relative strength abduction right |
| $rsABD^L$ | relative strength abduction rotation left |
| $rsER^R$ | relative strength external rotation right |
| $rsER^L$ | relative strength external rotation left |
| $rsIR^R$ | relative strength internal rotation right |
| $rsIR^L$ | relative strength internal rotation left |