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Acute Effects of Two Hip Flexor Stretching Techniques on Knee Joint Position Sense and Balance

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Abstract

The purpose of this investigation was to examine the acute effects of two hip flexor stretching techniques on hip extension ROM, knee joint position sense (JPS) and dynamic balance performance (DB). Thirty-six healthy college age students (25 males, 11 females; mean=22.39 years) who exhibited hip flexor tightness participated in this study. Hip extension ROM, knee JPS and DB were tested pre- and post-stretching using digital inclinometer, iPod touch and the Y-balance kit, respectively. Subjects were randomly divided into dynamic (DS), and hold-relax proprioceptive neuromuscular facilitation (HR-PNF) groups. Three-way mixed analysis of variance (ANOVA) was utilized to explore if an interaction between the groups (DS vs. HR-PNF), time (pre-and post) and (side of hip, knee angle and direction or reach) existed over the experiment as specified by hip extension ROM, knee JPS and dynamic balance measurements, respectively. There was a significant effect of time on hip extension ROM in both stretching groups (p<0.001). Also, there was a significant effect of stretch type on hip extension ROM (p=0.004) favoring HR-PNF over DS. There was a non-significant effect of time on mean knee JPS replication error in both groups. In dynamic balance measurement, there was a significant main effect of time on the Y-balance test's mean distance (p<0.001). There was also a significant main effect of directions of reach on distances achieved (p<0.001) favoring reach distance to posterolateral direction over posteromedial, and the latter over anterior direction. The results of this study demonstrated that dynamic and HR-PNF stretching techniques resulted in a significant acute improvement in hip extension ROM, dynamic balance measures. However, knee JPS replication error results showed nonsignificant improvement over time in either stretching group.

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Chapter I

The Problem and its Scope

Introduction

Tightness or restricted hip flexor muscle length, evaluated through hip extension range of motion (ROM) measurement, has been recognized as a risk factor for various musculoskeletal injuries (e.g., knee and hamstrings) in the lower extremities (Chumanov, Wille, Michalski, & Heiderscheit, 2012; Delp, Hess, Hungerford, & Jones, 1999; Gabbe, Bennell, & Finch, 2006; Kolber & Fiebert, 2005; Krivickas & Feinberg, 1996; Winters et al., 2004; Zeller, McCrory, Kibler, & Uhl, 2003). Tightness of hip flexor muscles refers to the inability of the individual to achieve full hip extension during the modified Thomas test position. A position that requires subjects lying on their back on a treatment table and holding one knee to the chest and letting the other leg to extend freely toward the floor at the end of the table. (Kendall, McCreary, & Provance, 1993). Limited hip extension ROM is thought to be a consequence of tight hip flexor muscles (Winters et al., 2004). Tight hip flexors is an impairment that has been found in individuals with lower-quarter (i.e. lower extremity) symptoms and functional limitations in addition to those who are free of lower- quarter symptoms (Offierski & MacNab, 1983; Winters et al., 2004). Lack of flexibility may cause early muscle fatigue or alter normal movement patterns (Krivickas & Feinberg, 1996). Therefore, tightness of hip flexor muscles (i.e. iliopsoas and rectus femoris) is believed to have negative impacts on dynamic balance as well as on dynamics of lower extremities, which in turn can increase the risk of falls (Endo & Sakamoto, 2014; Rodacki, Souza, Ugrinowitsch, Cristopoliski, & Fowler, 2009).

Tight hip flexors have been negatively correlated with dynamic balance performance in junior high school students (Endo & Sakamoto, 2014). Balance is a crucial element for recreationally active individuals, athletes, children and elderly. Several studies have indicated an association between diminished balance and injury (Docherty, Valovich McLeod, & Shultz, 2006; McGuine, Greene, Best, & Leverson, 2000; Nelson et al., 1994; Söderman, Alfredson, Pietilä, & Werner, 2001; Tropp, Ekstrand, & Gillquist, 1984). Balance and joint position sense (JPS) are proprioceptive parameters that rely on contributions from visual, vestibular and peripheral receptors (mechanoreceptors) that are found in skin, joints, muscles and ligaments (Bisson, McEwen, Lajoie, & Bilodeau, 2011; Gear, 2011; Gribble & Hertel, 2004; Gstöttner et al., 2009; Ribeiro, Mota, & Oliveira, 2006; Sotnikov, 2006; Voight, Hardin, Blackburn, Tippett, & Canner, 1996; Winter, Patla, & Frank, 1990). These receptors receive signals in response to mechanical stimulations that are transmitted through the afferent pathways via the spinal cord to be processed centrally in the brain (Johnson, Babis, Soultanis, & Soucacos, 2008; Winter et al., 1990). Proprioception provides the body with conscious and subconscious awareness of joint position and motion (Herter, Scott, & Dukelow, 2014; van der Wal, 2009) .

Proprioception is essential for knee joint functioning to maintain optimal control (balance) of lower extremities while performing different daily activities such as standing, walking and running (Bennell et al., 2003). JPS as an aspect of proprioception plays an important role in functional dynamic stability of the joint through the action of the muscles and ligaments around it throughout its ROM (Lephart, Pincivero, Giraldo, & Fu, 1997; Miura et al., 2004; Riemann & Lephart, 2002b; van der Wal, 2009). Reduced contributions from sensory proprioceptive receptors may diminish the protective reflex mechanisms of muscles (Sjölander, Johansson, & Djupsjöbacka, 2002). Further, diminished proprioceptive ability could predispose individuals to musculoskeletal disorders by altering the control of movement (Sharma, Pai, Holtkamp, & Rymer, 1997a).

Since hip flexor tightness is associated with balance problems, and because the proprioceptive aspect of JPS is one of the mechanisms that contributes to maintenance of balance, it is reasonable to question if restricted hip flexors have some unfavorable effects on the knee JPS. Having the rectus femoris muscle acting on both joints (Marieb & Hoehn, 2010) provides further support for this notion because this muscle functions as hip flexor and knee extensor. Moreover, similar to the relationship between tight hip flexors and lower extremity injuries, abnormal knee JPS has also been linked to several orthopedic and musculoskeletal conditions in the knee joint (Baker, Bennell, Stillman, Cowan, & Crossley, 2002; Beard, Kyberd, Fergusson, & Dodd, 1993; Hurley, 1997; Sharma, Pai, Holtkamp, & Rymer, 1997b). All of these factors could make the impairment of tight hip flexors one of the major parts in the vicious cycle of reduced balance, declined knee JPS ability and increased risk of lower extremity injuries.

In rehabilitation practice, stretching of hip flexor muscles has been acknowledged as effective in reversing limited hip extension ROM (Watt et al., 2011; Winters et al., 2004). A variety of stretching techniques have been described in the literature including dynamic, static, and hold-relax proprioceptive neuromuscular facilitation (HR-PNF) to address this impairment (Malai, Pichaiyongwongdee, & Sakulsriprasert, 2015; Winters et al., 2004). Stretching techniques have been widely used and recognized as a tool to stimulate core body and muscle temperature, enhance muscle strength, improve hip extension ROM, increase abdominal muscle activation, decrease low back pain and lumbar lordosis angle, increase lumbar stability, enhance knee JPS, and improve balance and coordination (Azeem & Sharma, 2014; Ghaffarinejad, Taghizadeh, & Mohammadi, 2007; Godges, Macrae, Longdon, Tinberg, & Macrae, 1989;

Godges, MacRae, & Engelke, 1993; Malai et al., 2015; Pasanen, Parkkari, Pasanen, & Kannus, 2009; Shellock & Prentice, 1985; Winters et al., 2004; Witvrouw, Mahieu, Danneels, & McNair, 2004). However, the effectiveness of static stretching (SS) has been questioned in recent years due to its adverse effect on performance (Chaouachi et al., 2008; Faigenbaum, Bellucci, Bernieri, Bakker, & Hoorens, 2005; McNeal & Sands, 2003; Yamaguchi, Ishii, Yamanaka, & Yasuda, 2007). Dynamic stretching (DS) incorporates a concomitant active contraction of antagonist muscles. This may in turn, lead to benefits to those muscles that are not experienced with static stretching (Winters et al., 2004). Therefore, and due to its distinct benefits on muscular performance, DS has been increasingly suggested as superior stretching technique (McMillian, Moore, Hatler, & Taylor, 2006; Moradi, Rajabi, Minoonejad, & Aghaei, 2014; Yamaguchi & Ishii, 2005). PNF stretching on the other hand, is considered one of the most effective stretching techniques used to improve ROM, particularly in respect to short-term changes in ROM (Roberts & Wilson, 1999; Sharman & Cresswell, 2006).

Although the exact mechanisms related to the acute effects of stretching on balance performance and accuracy of knee JPS are not clear, increased heart rate as well as core and muscle temperature, improved neural stimulation and proprioception, and increased neuromuscular activity that possibly linked to post-activation potentiation (PAP) were suggested as possible mechanisms behind improved balance performance and knee JPS (Behm & Chaouachi, 2011; Chumanov et al., 2012; Fletcher & Jones, 2004; Jaggers, Swank, Frost, & Lee, 2008; Sale, 2004; Yamaguchi & Ishii, 2005). Nonetheless, more research is specifically needed to evaluate the effects of dynamic and PNF stretching techniques on balance and knee JPS. If PNF and dynamic stretching techniques can positively influence these variables, then, these techniques could be used to improve performance in both physically active people and athletes as well as to the possibility of using them in rehabilitating tight hip flexors and hip injuries.

Purpose of the Study

The purpose of this study was to examine the acute effects of two hip flexor stretching techniques (dynamic and hold-relax proprioceptive neuromuscular facilitation) on hip extension ROM, knee joint position sense and dynamic balance performance in healthy college age students who exhibit hip flexors tightness. Further, we wanted to determine which one of these techniques has a greater influence on hip extension ROM, knee JPS and dynamic balance performance.

Hypothesis

The experimental hypotheses state that: there will be significant differences in hip extension ROM, knee JPS and dynamic balance measurements prior to and following the two stretching protocols. Also, there will be significant differences in hip extension ROM, knee JPS and dynamic balance measurements at post intervention time point between the two stretching groups.

Significance of the Study

Restricted or tightness of hip flexor muscles has been acknowledged as a risk factor for various lower extremity musculoskeletal injuries. However, this tightness is proven to be improved by stretching the hip flexor muscles. Therefore, using the more effective stretching techniques may lead into a greater health benefits than using other stretching techniques. Studies which have investigated the acute effects of dynamic stretching on dynamic balance and knee JPS are scarce or nonexistent to the researcher’s knowledge. Moreover, no research has investigated the effects of a widely used dynamic and proprioceptive neuromuscular facilitation stretching techniques on knee JPS and dynamic balance despite the intimate relationship between them as both being proprioceptive parameters. Based on the results of this study, the acute effects of these two stretching techniques on dynamic balance and knee JPS in healthy college age student population will be determined. The novel insight this study provides of how these two stretching techniques improve hip extension ROM, knee JPS and dynamic balance performance is very important. Thus, gaining a better understanding of their effects in this study would possibly lead to adopt these techniques to improve other health and fitness aspects in athlete and non-athlete populations of different ages.

Limitations of the Study

1. The age range of this study was limited to college age (18-28 years old), which limits the generalization of its results and its application to older or younger populations.
2. Having a fewer number of female than male participants in this study (11 females, 24 males) also limits the generalization of its results.
3. Participants started the study with different degrees of bilateral hip flexors tightness which may have affected the outcomes of this study. However, to decrease this effect, the primary inclusion criterion included only the subjects who demonstrated hip extension ROM between 5 to 15 degrees above the horizontal line during the modified Thomas test.
4. Dynamic balance ability and accuracy of knee JPS among the participants were also varying during the baseline measurements of the study, which may have affected the results. Despite the nonsignificant differences noticed between stretching groups at baseline measurements in all the three variables of the study, standard deviation values within each group were not small.

5. Repeating the pre- and post-intervention tests within 45-50 minutes could have had a learning effect on the performance during the dynamic balance and knee JPS tests. However, randomizing the order of these tests and trials within them was aimed to limit this effect.
6. Participants were informed not to exercise 24 hours prior to research experiments. While the majority followed this requirement, but we had no way of confirming this.

Definition of Terms

Absolute error (AE): The variable that reflects the accuracy of JPS, it refers to the difference between the target and estimated position (i.e. the measure of the magnitude of the error, discounting the direction) while assessing position sense of joint (Arvin et al., 2015; Olsson et al., 2004; Vafadar, Côté, & Archambault, 2015).

Autogenic inhibition: The reduction of excitability of a stretched or contracting muscle or group of muscles (Sharman & Cresswell, 2006).

Constant error: The variable that reflects the accuracy of JPS, it refers to the measure of the deviation from the target including the direction of deviation (i.e. overshooting + and undershooting – the target angle) (Vafadar et al., 2015).

Dynamic balance: The ability to perform a task while maintaining a stable position (Winter et al., 1990).

Dynamic stretching: The performance of controlled movements through the active range of motion of a joint while moving within the extensibility limits of the individual (Fletcher & Jones, 2004).

Flexibility: The joint's ability to pass through a given range of motion without significant restriction or impingement (ACSM, 2014).

Golgi tendon organs (GTOs): Type of mechanoreceptors located near the musculotendinous junctions and are sensitive to skeletal muscle contraction (Jami, 1992; Moore, 1984).

Joint position sense: An aspect of proprioception; the sense of the static position of a joint or body part (Herter et al., 2014).

Kinesthesia: An aspect of proprioception; the ability to identify a body motion or movement rate of a joint (Gilman, 2002; Herter et al., 2014).

Mechanoreceptor: Types of peripheral receptors located in the connective tissues that enable the sense of joint position, the sense of touch and proprioceptive awareness involving muscle length (Kandel, Schwartz, & Jessell, 2000).

Muscle spindles: Fusiform (spindle-shaped) proprioceptors found in skeletal muscle, they are sensitive to length and rate of length changes. (Lephart et al., 1998; Marieb & Hoehn, 2010).

Post-activation potentiation: The phenomenon by which the contractile history of a muscle affects the mechanical performance of subsequent muscle contractions (Bishop, 2003; Lorenz, 2011; Robbins, 2005).

Proprioception: The combination of joint position sense and kinesthesia; the ability to perceive the location of the body (i.e. joint position and motion) in space consciously and subconsciously (Gilman, 2002; Herter et al., 2014; van der Wal, 2009).

Proprioceptive neuromuscular facilitation stretching: The combination of passive stretch and isometric contractions of the target muscle; is commonly used to improve the joint ROM, muscular strength, and neuromuscular control by a therapist in clinical and rehabilitation settings (Marek et al., 2005).

Reciprocal inhibition: The phenomenon that occurs when a voluntary contraction of the opposing or antagonist muscle results in reduced activation levels in the target or agonist muscle (Sharman & Cresswell, 2006; Youdas et al., 2010).

Static balance: The ability of the body to maintain a base of support with a minimal movement. These movements are expressed in the mediolateral and anteroposterior directions and usually measured by a force platform by calculating ground reaction forces (Palmieri, Ingersoll, Stone, & Krause, 2002; D. A. Winter et al., 1990).

Sense of effort: An essential component of all forms of exercise, it refers to a signal of central origin that provides positional information on body segments based on the effort required to maintain the position (Smirmaul, 2012; J. Winter, Allen, & Proske, 2005).

Tight hip flexors: The lack of ability of an individual to achieve a full hip extension when being tested by the modified Thomas test (Kendall, McCreary, & Provance, 1993).

Chapter II

Review of Literature

Introduction

This study investigated the acute effects of two hip flexor stretching techniques (hold-relax proprioceptive neuromuscular facilitation (HR-PNF) and dynamic stretching (DS) on knee joint position sense (JPS) and balance. This chapter starts with an anatomical description of major hip flexor muscles. Then, continues in exploring hip flexor tightness and measurement of hip extension range of motion (ROM). Discussion about proprioception, balance and their mechanisms as well as measurements follows next. The relationship between tight hip flexors and balance then stretching techniques with emphasis on HR-PNF and DS techniques were also investigated in this chapter. The last three sections of this literature review focused on the studies which investigated the acute effects of stretching on hip extension ROM, balance and knee JPS. Studies were compared based on their findings with respect to their acute effects on these three variables, and mechanisms suggested behind these effects.

Anatomy of Major Hip Flexor Muscles

Iliacus (IL), psoas major (collectively known as the iliopsoas) and rectus femoris (RF) are the three more recognizable primary hip flexor muscles (Neumann, 2010; Simonsen et al., 2012) and the most reported in literature (Kobetic, Marsolais, & Miller, 1994). Among these muscles, iliopsoas is the most prominent and strongest hip flexor in humans (Hogervorst & Vereecke, 2014; Neumann, 2010). This muscle is formed when the psoas major muscle joins with iliacus muscle, which continues over the superior ramus of the pubic bone to have its final insertion on the lesser trochanter (Tufo, Desai, & Cox, 2012). This thick muscle produces force across the hip, sacroiliac joint, lumbosacral junction, and lumbar spine. Because the muscle spans both the axial and appendicular components of the skeleton, it functions as a hip flexor as well as a trunk flexor (Neumann, 2010).

The psoas major muscle is a long, thick and more medial muscle (Marieb & Hoehn, 2010). The psoas major attaches to the T12-L4 vertebral bodies and the L1-L5 transverse processes at its origin. Its primary role is to flex the hip, but it also plays a role in side bending of the spine (Tufo et al., 2012). The psoas major plays an important role in the vertical stability of the lumbar spine, especially when the hip is in full extension and passive tension is greatest in the muscle (Gyoung-Mo Kim & Sung-Min Ha, 2015; Neumann, 2010). In individuals who have a psoas minor muscle, this muscle usually attaches to the T12-L1 vertebral bodies at its origin and inserts at the iliac fascia bilaterally. The psoas minors action is to assist the psoas major muscle in flexion of the hip and lumbar spine (Tufo et al., 2012).

The iliacus muscle is a large, fan shaped and more lateral muscle that originates from the iliac fossa and crest, and ala of sacrum (i.e. the wing-like shaped superior-lateral region of the sacrum) and inserts on the lesser trochanter of femur via the iliopsoas tendon. Along with psoas major, it functions as a prime mover for flexing the thigh or flexing trunk on thigh (Marieb & Hoehn, 2010). The rectus femoris is a superficial muscle within the quadriceps femoris muscle (Marieb & Hoehn, 2010). It is a bi-articular muscle that spans over the hip and knee joints (Hogervorst & Vereecke, 2014). Rectus femoris originates from the anterior inferior iliac spine and superior margin of acetabulum, and inserts into the patella and tibial tuberosity via patellar ligament (Marieb & Hoehn, 2010). Besides being a powerful knee extensor, rectus femoris also functions as a relatively weak hip flexor (Hogervorst & Vereecke, 2014).

Tight Hip Flexors

Flexibility is a crucial element for a normal biomechanical functioning, and it is a muscle or a group of muscles' ability to lengthen, permitting a joint or more to move within its normal ROM (Hopper, 2005; Yıldırım, Ozyurek, Tosun, Uzer, & Gelecek, 2016). On the contrary, inability of an individual to achieve a full hip extension when demonstrating the modified Thomas test position is defined as tightness of the hip flexor muscles (Kendall et al., 1993; Winters et al., 2004). Also, tightness of the capsule-ligamentous structures around the anterior hip may contribute to decreased hip extension flexibility and in turn result in positive test. (Florence Peterson Kendall, McCreary, Provance, Rodgers, & Romani, 2005). This impairment (i.e., limited hip extension ROM) is prevalent not only in individuals who suffer from lower-quarter symptoms and functional limitations but even among those who are free of these symptoms (Winters et al., 2004). Besides the proper length of the hip flexor muscles, the extensibility of the anterior ligaments of the hip is also important contributing factor in the efficiency of daily activities such as walking (Godges et al., 1993).

The primary hip flexor (iliopsoas muscle) is slightly hypertonic (i.e., tight) in most individuals. This hypertonicity is specifically apparent in athletes, such as runners, who frequently use their psoas major muscle during practice and competition (Tufo et al., 2012). Since the iliopsoas functions as a major compressor of the lumbar spine, and maintains the stability of the spine because of its comprehensive nature as it spans from the thoracolumbar region, across the lumbar spine and pelvis, to the femur attachment, too much compression (clinically known as iliopsoas tightness), can have a harmful effect on the spine's health (Avrahami & Potvin, 2014). Tightness of the iliopsoas and other hip flexors can result in an anterior pelvic tilt and exaggerated lumbar lordosis which in turn may cause low back pain (Liemohn & Pariser, 2002; Neumann, 2010; Tufo et al., 2012).

Measurement of hip extension ROM. This measurement is a part of the overall hip ROM measurements that is commonly used to quantitatively assess hip joint mobility. This clinical variable often evaluated in conditions such as arthritis of the hip, patellofemoral and low back pain (Holm et al., 2000; Roach et al., 2015; Roach, San Juan, Suprak, Lyda, & Boydston, 2014). Hip extension ROM is usually tested using the modified Thomas test position (Ferber, Kendall, & McElroy, 2010; Godges et al., 1993; Gyoung-Mo Kim & Sung-Min Ha, 2015). Unlike the original Thomas test, the modified Thomas allows the tester to observe both the knee and hip angles (Clapis, Davis, & Davis, 2008). The modified Thomas test has been previously found to be adequately reliable when measuring healthy individuals (Bartlett, Wolf, Shurtleff, & Stahell, 1985). The prevalence of its use may likely due to its relative ease of use, as well as its low cost and portability (Roach, San Juan, Suprak, & Lyda, 2013).

During the modified Thomas test, the subject lies supine with the hip joint positioned over the edge of the examination table. Then, the subject flexes the hip, bringing one of the knees to the chest and holding it while the low back, sacrum, and pelvis remain flat against the surface of the table. When subject’s opposite thigh shows inability to extend to a neutral position or drop below the horizontal line, also when subject fails to reach 80 degrees of knee flexion, the test considered to be positive (Ferber et al., 2010; Godges et al., 1993).

Instruments such as digital photography, goniometers and digital inclinometers have systematically been used in the literature to measure hip extension ROM (Avrahami & Potvin, 2014; Gyoung-Mo Kim & Sung-Min Ha, 2015; Mills et al., 2015; Roach et al., 2013; Winters et al., 2004). In a more recent investigations, universal goniometers and digital inclinometers are increasingly used for measuring hip extension ROM (Avrahami & Potvin, 2014; Ferber et al., 2010; Mills et al., 2015; Roach et al., 2013). One positive factor is that the utilization of goniometer with hip measurement has been reported to demonstrate concurrent validity when compared to 2D video motion capture system (Moreside & McGill, 2011). Also, measurements using goniometer have a good intra-rater reliability with Intra-class Correlation Coefficients (ICC>0.80). However, inter-rater reliability is generally poor (ICC<0.50), which adds a limitation to the measurement when using goniometers (Boone et al., 1978; Clapis et al., 2008; Herrero, Carrera, García, Gómez-Trullén, & Oliván-Blázquez, 2011; Watkins, Riddle, Lamb, & Personius, 1991). Further, the use of the universal goniometer has a limitation represented by requiring both hands during measurement which makes the stabilization of other body parts difficult. This difficulty gets more obvious when only one investigator is measuring joint angles such as isolated hip and knee range of motions as it has been suggested that soft tissue constraints and contributions of the lumbo-pelvic region may limit attaining accurate measures (Gajdosik & Bohannon, 1987; Nussbaumer et al., 2010; Peeler & Anderson, 2008).

The digital inclinometer is another device that has increasingly been utilized by some clinicians and researchers to measure hip extension ROM in recent years. Despite the higher cost of this device compared to goniometer, its lightweight, portability and capability to provide real-time digital reading of angles in a 360 degree are obvious advantages (Roach et al., 2015, 2014; Roach et al., 2013; Young et al., 2014). Also, when digital inclinometer is used to measure hip ROM's, it only requires the use of one hand, this enables the other hand to stabilize the lumbar spine to ensure accurate measurement. In addition, good inter-rater reliability (ICC>0.80) was reported using this device (Kolber, Vega, Widmayer, & Cheng, 2011). According to the investigations examining both hip and shoulder joints, good to excellent reliability (ICC>0.88) and concurrent validity with the universal goniometer (ICC>0.85) was reported in measurements utilizing digital inclinometer (Clapis et al., 2008; Kolber & Hanney, 2012; Mills et al., 2015). In several studies conducted on healthy individuals and patients with cerebral palsy, good reliability was demonstrated for measurements of hip joint ROM using digital inclinometer (Boyd, 2012; Herrero et al., 2011; Mills et al., 2015). Finally, the decision of selecting what instrument to use in measuring ROM of the target joint or joints should logically consider factors such as ease of use, clinical availability, skill level of the investigator as well as factors related to reliability and reproducibility (validity) (Roach et al., 2013)

Proprioception

Proprioception is a vital part of the somatosensory system. Proprioception denotes the ability of human's body to perceive its location in space consciously and subconsciously and it encompasses JPS, the sense of the static positon of a joint, and kinesthesia, the awareness of joint position during a passive or active movement of a limb (Herter et al., 2014; Hiemstra, Lo, & Fowler, 2001; Johnson et al., 2008; Proske, 2006; Proske & Gandevia, 2012; van der Wal, 2009). Proprioception represents the total neural input sent from specialized nerve endings called proprioceptors or mechanoreceptors to the central nervous system. These mechanoreceptors (i.e. interocepetors which perceives stimulations in our body) are located in the muscles, ligaments, tendons, joint capsules and skin (Gear, 2011; Ribeiro et al., 2006; Sotnikov, 2006; Voight et al., 1996). They are sensitive to changes in stretch, and their role is to transmit information about joint position and body movement to the central nervous system (CNS) for interpretation and evaluation (Docherty, Arnold, Zinder, Granata, & Gansneder, 2004; Gear, 2011; Johnson et al., 2008; Lee, Liau, Cheng, Tan, & Shih, 2003). Proprioception also controls body balance, especially, JPS which plays a major role in maintaining functional dynamic stability of the joint which is controlled by the acting muscle and ligaments around it throughout the ROM (Kavounoudias, Roll, & Roll, 2001; Lephart et al., 1997; Miura et al., 2004; Riemann & Lephart, 2002b; van der Wal, 2009). Therefore, JPS and balance are intertwined parameters because they are both proprioceptive aspects and reliant on mechanoreceptors that transmit proprioceptive information about JPS and change in muscle length (Kandel et al, 2000). In addition, sense of effort is also reliant on receptors linked to proprioception (Proske & Gandevia, 2012). Utilizing afferent information provided by these proprioceptors, the CNS conveys efferent signals to muscles that lead to a muscle action or does not send efferent signals resulting in relaxation of the muscle (Gear, 2011).

Within the topic of proprioception, the following subsections will cover the primary peripheral components of proprioception and mechanisms that contribute to JPS. In addition, central processing of proprioception, knee JPS and how JPS is measured will also be explored.

Peripheral components of proprioception. According to literature, mechanisms related to proprioception are based on information transmitted by a number of peripheral receptors. These mechanoreceptors are special nerve endings that depolarize in response to mechanical deformation of tissue that is then converted into neural signals (Grigg, 1994). Mechanoreceptors include muscle spindles, Golgi-tendon organs (GTOs), Ruffini endings, the Pacinian endings, and the primary sensory pathways that deliver signals through the spinal cord to the motor cortex in the brain (Johnson et al., 2008; Marieb & Hoehn, 2010; Proske & Gandevia, 2012). These mechanoreceptors are located in certain locations and have their own specific functions. The Ruffini endings and Pacinian corpuscles are abundant in ligaments, tendons, joint capsules and loose connective tissue next to dense connective tissues (Marieb & Hoehn, 2010; Yahia, Rhalmi, Newman, & Isler, 1992). Ruffini endings' role is to indicate the limit of motion of a joint and respond to deep pressure and stretch, while Pacinian corpuscles respond to deep pressure, stretch, vibration or movement of high frequency in order to detect rate of motion. Golgi tendon organs from their name are located in tendons, and they are stimulated by both tension and stretch (Johnson et al., 2008; Marieb & Hoehn, 2010). Generally, it is a widely accepted notion that the most crucial determining factor in joint proprioception are muscular mechanoreceptors (muscle spindles) that are located in muscles and responsible for movement and joint control (Proske, 2006).

Knee joint mechanoreceptors. The function of proprioceptive mechanoreceptors is a crucial element for position sense. Mechanoreceptors found in the knee joint include GTOs, free nerve endings, Pacinian corpuscles and Ruffini endings (Halata, Rettig, & Schulze, 1985; Lephart, Swanik, & Boonriong, 1998). GTOs are found in the cruciates, collateral ligaments, and menisci. GTOs remain inactive when joint is not moving, but are stimulated at the extremes of joint motion. Free nerve endings are extensively covering most articular structures; they are sensitive to certain chemical by-products of the inflammatory process. With regard to mechanical changes in the knee joint, free nerve endings stay silent during normal conditions, however, they become active when articular tissues experience detrimental mechanical deformation (Lephart et al., 1998). Pacinian corpuscles are low-threshold, quick adapting mechanoreceptors found in the extra- and intra-articular fat pad, medial meniscus, anterior and posterior cruciate ligaments (ACL and PCL), meniscofemoral, and collateral ligaments. They are stimulated by deformation of tissue due to quick changes in velocity and direction in the initial and end phases of a joints ROM and their role is to mediate the sensation of joint motion (Katonis et al., 2008; Lephart et al., 1998; Voight et al., 1996). Ruffini endings are low-threshold, slow adapting mechanoreceptors (i.e. produce continuous and steady electrical activity discharge when triggered by continuous stimulus) (Riemann & Lephart, 2002a) located in the superficial layer of the cruciate, meniscofemoral, and collateral ligaments. Ruffini endings is believed to be stimulated by capsular stress and they facilitate the amplitude and velocity of joint rotation and position (Lephart et al., 1998; Voight et al., 1996).

Muscle spindles and Golgi tendon organs. Muscle spindles (fusiform) are found in skeletal muscle and are sensitive to length and rate of length changes. Each muscle spindle consists of a bundle of 3-10 folds of modified skeletal muscle fibers called intrafusal fibers enclosed in a capsule of connective tissue (Lephart et al., 1998; Marieb & Hoehn, 2010). These fibers have nuclear bag and chain that expand from the capsule to join the extracellular connective tissue or tendon (Hunt, 1990; Swash & Fox, 1972). Muscle spindles are wrapped by 2 types of afferent endings called primary and secondary endings. Nuclear bag has the primary endings while the nuclear chain contains the secondary endings, and both endings participate in JPS by the mean rate of background discharge. The primary endings are stimulated by the rate and degree of stretch in muscle length by synapsing in the spinal cord in order to convey information to the brain (i.e. cortex). The secondary endings are stimulated only by degree of stretch and particularly involved in the static position sense aspect of proprioception (Fallon & Macefield, 2007; Macefield, 2005; Proske & Gandevia, 2012; Swash & Fox, 1972). Muscle spindles are distinguished from other mechanoreceptors by being equipped with motor neurons (β-motoneurons. γ-motonerurons) from the CNS enabling them to modify the response of their endings to a particular stimulus (Allen, Ansems, & Proske, 2008; Hospod, Aimonetti, Roll, & Ribot-Ciscar, 2007; Hunt, 1990; Lephart et al., 1998; Swash & Fox, 1972). When signals from the gamma motor nerves increase, it intensifies muscle spindles sensitivity to stretch without initiating a muscle contraction. The stimulated muscle spindles transmit information related to joint position and motion that resulted from changes in muscle length, then the change in length is interpreted by CNS as a change in firing rate (Lephart et al., 1998; Marieb & Hoehn, 2010; Proske, 2005). Also, muscle spindles have the capacity to produce a reflex contraction of the agonist muscles through a mechanism known as the stretch reflex mechanism (Lephart et al., 1998; Marieb & Hoehn, 2010). Further, unlike the skin and joint receptors that contribute to kinesthesia, only muscle spindles are likely to display a muscle history dependence, as a result of the thixotropic behavior of the intrafusal fibers (Gooey, Bradfield, Talbot, Morgan, & Proske, 2000; Lephart et al., 1998). GTOs on the other hand, are class of mechanoreceptors that are sensitive to skeletal muscle contraction. GTOs are innervated by fast-conducting Ib afferent fibers (Jami, 1992). They are located near the musculotendinous junctions and mostly found at points of deep intramuscular tendons or aponeuroses and their function is to monitor muscle tension. When the muscle fibers that are connected to a series of tendon organ contract, they stimulate the GTO receptors by straining the collagenous bundle which involves deformation of sensory terminals (Jami, 1992; Moore, 1984). GTOs function in harmony with muscle actions, therefore, when stimulated by a high muscle tension, they cause relaxation of the involved muscle through reflexive inhibition (Lephart et al., 1998; Marieb & Hoehn, 2010).

Skin Mechanoreceptors. Meissner corpuscles, Pacinian corpuscles, Merkel endings and Ruffini endings are the types of specialized mechanoreceptors found in skin. These receptors' main function as a skin afferents is to enhance the effects of other proprioceptive inputs that maintain proprioception and motor control through its mechanosensitive endings (Lephart et al., 1998; Macefield, 2005; Proske & Gandevia, 2012). All of these receptors are likely involved in movement sensations, however, Ruffini endings (i.e. the skin stretch receptors), are potentially able to sense limb position (Proske & Gandevia, 2012). Contrary to the previous opinions which stated that muscle spindles are the foremost kinesthetic receptor (Proske, 2005, 2006; Proske & Gandevia, 2012) also that cutaneous receptors may likely be less influential than joint receptors and muscle spindles in proprioception (Johansson & Vallbo, 1983; Lephart, Pincivero, & Rozzi, 1998), a recent study demonstrated that stretching of the skin surrounding joints amplified the movement elusion triggered by vibration of the muscle spindles in the prime movers by 1.4-1.5 times compared to vibration alone. (Collins, Refshauge, Todd, & Gandevia, 2005).

Central processing of Proprioception. Many ascending and descending pathways connect the peripheral nervous system (PNS) to the brain through lower spinal center to carry signals between these two parts of the nervous system. These coded signals follow the afferent (ascending) tracts to 3 stages of motor control: the cerebral cortex, brain stem, and spinal reflexes (Lephart et al., 1997). Information transmitted from visual, proprioceptive and tactile senses to the dorsal premotor cortex in the brain contribute to the proprioceptive aspect of joint position sense (Johnson et al., 2008; Lephart et al., 1997). The information is encoded for the CNS not by individual receptors but by populations, this property called ensemble coding (Johansson, Sjölander, & Sojka, 1991). After afferent and efferent information about a movement are combined in the cerebellum, they are then blended to be centrally integrated. The latter step produces the primary site where limb position sense contributes to controlled movement (Johnson et al., 2008; Walsh, Smith, Gandevia, & Taylor, 2009). The information about the detected sensations by the peripheral receptors of the muscle arrives to the prefrontal cortex of the brain through spinal cord pathways to be evaluated for motor planning and transmitted to the premotor cortex (proprioception site) of the brain. The latter area obtains information from the motor nuclei which are located in the ventroanterior and ventrolateral thalamus, the primary somatosensory cortex and parietal association cortex as well as in the prefrontal association curve. Cerebellum and basal ganglia give feedback to the two thalamus parts mentioned earlier. Information related to the current motor response are then conveyed by the primary somatosensory cortex and parietal association cortex. Motor programs are produced and moved to the motor cortex after completing motor planning at the premotor cortex. Here, movements around the joints occur in the desired directions as a result of stimulated neurons. The occurrence of muscle actions and their timing are regulated by the communications between posterior and anterior association areas (Kandel et al., 2000; Lephart et al., 1998; Marieb & Hoehn, 2010).

Knee joint position sense. As a proprioceptive sense, knee JPS is regulated by central and peripheral mechanisms and predominantly determined by muscle receptors, however, tendinous, articular, cutaneous and anterior cruciate ligament receptors also contribute to knee JPS (Hiemstra et al., 2001; H. Johansson et al., 1991; Larsen et al., 2005; Lattanzio & Petrella, 1998; Proske, Wise, & Gregory, 2000). Generally, more proximal joints tend to be better in position sense than distal joints due to differences in muscle spindles number crossing each joint (Hall & McCloskey, 1983; Scott & Loeb, 1994). Thus, muscle spindles appear to play the dominant role in proprioception in proximal joints, while skin and joint inputs are more important at distal joints, like the finger joints (Proske et al., 2000). Also, it has been indicated that muscle mechanoreceptors may play a pivotal role in the mid-range of motion of the joint, however, receptors in the ligaments are more sensitive near the end limits of a joint’s motion (Gear, 2011).

Proprioception is essential for the knee joint to maintain better control of lower extremities while performing different daily activities such as standing, walking and running. Central control by brain awareness of knee joint position stimulates the muscles around the knee to contribute to the stability of knee joint as well as absorbing much of the load placed on it during sport activities (Bennell et al., 2003; Moradi et al., 2014). Therefore, decline in contributions from sensory receptors as well as delayed signals from CNS may unfavorably affect the protective reflex mechanisms of muscles (Löscher, Cresswell, & Thorstensson, 1996; Sjölander et al., 2002). Several musculoskeletal pathologic conditions have been linked to abnormal knee JPS. These pathological conditions include knee joint osteoarthritis (Hurley, 1997; Sharma et al., 1997b), anterior cruciate instability (Beard et al., 1993) and patellofemoral pain syndrome (Baker et al., 2002). Deficits in proprioceptive ability could predispose individuals to injuries by altering the control of movement (Roberts, Rash, Honaker, Wachowiak, & Shaw, 1999). For example, in knee joint with osteoarthritis, sensorimotor dysfunction may result in a greater impact on the leg at heel strike thus initiating or advancing arthritic damages (Radin, Yang, Riegger, Kish, & O’Connor, 1991; Sharma et al., 1997b). The dominant role that muscle mechanoreceptors play in JPS suggests that if the functional state of the muscles modified (e.g., improved by stretching), this may affect the performance accuracy of JPS (Bouët & Gahéry, 2000).

Measurement of JPS. JPS is the active or the passive replication of the position of a joint performed by a subject in closed and/or in open kinetic chain conditions (Ribeiro et al., 2006; Riemann & Lephart, 2002b). A reliable technique to assess JPS is to measure the replication of a specific target joint position or angle, then the difference between the target and estimated position is used as a value to reflect JPS accuracy of the join of interest. The difference is specified as the absolute error (AE) which reflects the measure of accuracy of JPS (Arvin et al., 2015; Olsson et al., 2004). Usually, JPS is assessed while the subject is performing both target and estimated joint angles with a blocked vision and unassisted (Moradi et al., 2014; Ribeiro et al., 2006; Sun-Ik, Dong-Yeop, Ji-Heon, Jae-Ho, & Jin-Seop, 2015).

Studies investigating JPS have been utilizing various techniques and devices to measure the conscious submodalities of proprioception such as JPS. Direct and indirect techniques have been used to assess JPS. Inclinometers and goniometers have increasingly been utilized to directly measure JPS, while less commonly, visual analog scale systems used to indirectly measure the same parameter (Riemann, Myers, & Lephart, 2002). Common devices and tools used to measure JPS include electrogoniometers, universal goniometers, commercial isokinetic dynamometers, electromagnetic tracking devices, custom-made apparatuses, Apple iPods integrated with custom-made software, potentiometers, video and visual analog scales as well as systems that are designed by investigators themselves (Eils & Rosenbaum, 2001; Erden, 2009; Larsen et al., 2005; Moradi et al., 2014; Ribeiro et al., 2006; Riemann et al., 2002; Smith, Crawford, Proske, Taylor, & Gandevia, 2009; Sun-Ik et al., 2015; Viera, 2015; Walsh et al., 2009). Among these devices, inclinometers, Apple iPods and mobile phones, that can directly measure ROM and JPS are being increasingly used because they are inexpensive, reliable and easy to use (Dover & Powers, 2003; Mourcou et al., 2015; Viera, 2015).

With regard to assessing knee JPS, ipsilateral is favored over contralateral measurement and sitting is favored over prone position (Bouët & Gahéry, 2000; Larsen et al., 2005). Also, an active/active protocol is preferred while assessing JPS because it is more accurate and repeatable, minimizes the AE, and possibly more reflective of the sensory experience during the normal movement patterns of real life activity. Active/active protocol implies that the assessed client is actively performing both the target and estimated positions. (Arvin et al., 2015; Boerboom et al., 2008; Kalaska, 1994; Laufer, Hocherman, & Dickstein, 2001; Lönn, Crenshaw, Djupsjöbacka, Pedersen, & Johansson, 2000). Despite that AE provides a general expression of the amount of error between the target and estimate positions, however, identifying overestimation or underestimation (i.e. constant error, CE) of the target position by tested individual has its importance (Larsen et al., 2005).

In a summary, all of the aforementioned proprioceptive mechanoreceptors play a role in proprioception in human body. The role they play depends on their locations, level of innervation, types of tissues they are arising from and the types of stimulus sensitive to. Overall, the perceived information by cutaneous, muscle, GTOs and joint receptors makes human's body distinguish the location of a limb and the time associated to that location. Proprioception is related to the motor programming required for accuracy of movements and contributes to muscle reflex, providing dynamic stability for the joint. Therefore, proprioceptive sensing is vital for balance ability during regular daily activities and sports. JPS is a major aspect of proprioception that reflects how accurately the peripheral proprioceptors transmitting information to the central nervous system and how this information is interpreted centrally. Proprioception can be assessed objectively by measuring JPS which usually involves a procedure where a target joint position is required to be replicated. This technique has been demonstrated to be both valid and reliable assessment of proprioception (Arvin et al., 2015; Dover & Powers, 2003).

Balance

Maintenance of balance and equilibrium is an essential component of daily activities for human. This is dependent on complex reflexive involvements initiated by vestibular, visual, and somatosensory (proprioceptive) systems and coordinated continuously by the CNS (Bisson et al., 2011; Gribble & Hertel, 2004; Gstöttner et al., 2009; Winter et al., 1990). Proprioception is one of the crucial contributors to control of postural stability (Di Giulio, Maganaris, Baltzopoulos, &

Loram, 2009), and since JPS is an aspect of proprioception (Herter et al., 2014), therefore balance and JPS are closely related and both considered proprioceptive parameters (Kaminski & Perrin, 1996; Kandel et al., 2000).

Mechanisms. Balance and control of posture relies possibly on contributions from visual and somatosensory systems of the CNS, however, balance is also regulated by the vestibule-spinal reflexes which use the simple pathways of the vestibular system. As balance tasks get harder, vestibulo-spinal reflexes heighten their involvement to maintain equilibrium, and undesired joint oscillations decrease due to reduction in H-reflex response (Angelaki & Cullen, 2008; Lephart et al., 1998). With regard to the somatosensory system contributions to maintain balance, this system receives input from articular, cutaneous, and musculotendinous receptors. The latter send afferent signals regarding changes in length and tension within the muscle and tendon. Musculotendinous receptors include muscle spindles and Golgi tendon organs (Gribble & Hertel, 2004). If function of one or all of physiological mechanisms are altered, balance performance may be negatively affected which may predispose individuals to increased risk of injury (Roberts et al., 1999).

Balance can be divided into static and dynamic balance (Winter et al., 1990). Dynamic balance requires the use of pertinent internal and external information to react to perturbations of stability and also requires activation of muscles to work in coordination to anticipate changes in balance (Spirduso, 1995). Since the focus of the present study is on dynamic balance performance, the sole emphasis here is on how dynamic balance could be measured objectively using the Star Excursion Balance Test (SEBT).

Measurement of dynamic balance. Different dynamic balance measurement instruments and tests are regularly used in both research and clinical settings. SEBT, Biodex

Balance System SD (SD=static and dynamic) and wobble board are among other tests used to measure dynamin balance. Dynamic balance tests mimic more closely demands of physical activity than static balance assessments (Amiri-Khorasani, 2015; Azeem & Sharma, 2014; Gribble, Hertel, & Plisky, 2012; Handrakis et al., 2010).

SEBT is a clinical procedure utilized to assess dynamic balance ability. It is commonly used in research applications as well as for injury evaluation and as a therapeutic exercise in rehabilitation settings (Gribble, Kelly, Refshauge, & Hiller, 2013; Hertel, Miller, & Denegar, 2000; Kinzey & Armstrong, 1998). SEBT has been proven to be an easy and feasible test that sufficiently challenges athlete's ability for dynamic balance, to assess improvements in dynamic postural control after exercise interventions, and proven to be a clinical application to predict the risk of injury to lower extremity (Gribble et al., 2013; Hertel et al., 2000; Kinzey & Armstrong, 1998; Plisky, Rauh, Kaminski, & Underwood, 2006). SEBT usually contains a series of lower extremity reaching tasks in 8 directions (anterior, anteromedial, anterolateral, medial, lateral, posterior, posteromedial, and posterolateral) from the center of the grid that requires individual’s postural control, range of motion, coordination, strength and proprioceptive abilities. These 8 reaching tasks are performed using a single-leg stance on one leg with maximum reach of the opposite leg. The farther distance the touching leg reaches, the better dynamic balance it displays. The ability to reach farther with the touching leg also requires a combination ability of better dynamic balance on the contralateral stance leg (Hertel et al., 2000). In an effort to simplify SEBT and to determine which components of the SEBT are most affected by chronic ankle instability (CAI), Hertel, Braham, Hale, and Olmsted-Kramer, 2006 reduced reaching tasks to only anterior, posteromedial, and posterolateral directions (i.e. the Y excursion balance test, YEBT). High to excellent intra-tester and inter-tester reliability of the SEBT had previously been reported in assessing dynamic balance. The intra-class correlation coefficients were ranging from 0.85-0.96 for intra-tester reliability and from 0.86-0.93 for inter-tester reliability (Gribble et al., 2013; Hertel et al., 2000; Kinzey & Armstrong, 1998).

To validate comparisons of SEBT measurements among tested individuals, it is required to normalize reaching distances to individual's limb length as measured from the anterosuperior iliac spine to the medial malleolus (Gribble & Hertel, 2003). Not only limb length, but a number of physiological and anthropometrical factors including ROM, fatigue, and interventions could potentially contribute to SEBT performance. However, in recent years, increasing number of studies started to use SEBT to measure dynamic balance in different populations including athletes, healthy active young male and female adults and even individuals with certain pathological conditions. In these studies, SEBT was either used following its original 8 directions or the reduced configuration (i.e. 3 or 4 directions; Y or +) (Amiri-Khorasani, 2015; Azeem & Sharma, 2014; Bressel, Yonker, Kras, & Heath, 2007; Endo & Sakamoto, 2014; Gribble et al., 2013; Hertel et al., 2006).

Relationship between Balance and Tight Hip Flexors

The core region and specifically core musculature plays an important role in controlling the position of the upper limbs and stabilizing the lower extremities as well as knee movements during activity (Ambegaonkar, Mettinger, Caswell, Burtt, & Cortes, 2014; Willson, Dougherty, Ireland, & Davis, 2005); therefore, change in the length of any of the muscles in the core area may affect the ability to balance. Muscle length can affect the contractile characteristics of the muscle, and shortened or lengthened muscles may show decreased ability to generate maximum tension if their length during resting has been changed (Winters et al., 2004). Therefore, to maintain proper posture and equilibrium, muscles and ligaments should be in balance (Zagyapan et al., 2012). Further support for the relationship between balance and tight hip flexors came from a study conducted by Endo and Sakamoto (2014). Endo and Sakamoto reported significant negative correlation between the lateral direction (LAT reach) using SEBT and iliopsoas tightness in 33 junior high school male (mean=13.4 ± 0.5 years) baseball players.

Lumbar hyperlordosis and excessive anterior pelvic tilt were found to be primarily caused by shortening of the iliopsoas muscle (Jorgensson, 1993). Excessive anterior pelvic tilt is thought to be associated with excessive muscle length and weakness of the abdominal muscles (Godges et al., 1993). This abnormal alignment (i.e. tight hip flexors and reduced hip extension ROM) may inhibit the function of the core muscles such as transversus abdominis muscle (Malai et al., 2015), which may in turn, negatively affect the ability to balance (Choi, Kim, & Kim, 2013). Tight or weak hip flexors may not provide enough stability for the pelvis during activity such as in walking, which results in anterior tilt of the pelvis and concomitant femoral internal rotation (Tyler, 2006). Because iliopsoas muscle is a secondary femoral external rotator, weakness of this muscle may put the femur in an exaggerated internal rotation position, leading to misalignment of the trochlear groove with the patella (Tyler, 2006). The latter condition can contribute to imbalanced posture that leads to fatigue, skeletal asymmetry, and pain (Zagyapan et al., 2012), all of which can perturb the ability to balance. Further, it has been reported that insufficient balance can negatively affect athletic performance (Irrgang & Whitney, 1994) and increase the risk of injury (Hrysomallis, 2007; McGuine et al., 2000; Trojian & McKeag, 2006).

Stretching Techniques

To improve muscle flexibility and joint ROM, various stretching techniques have been described in the literature. These techniques have been developed and practiced in exercise training, sports competition as well as in rehabilitation settings. Stretching techniques include static stretching (SS), dynamic stretching, manual fascial-muscular lengthening therapy (FMLT) (i.e. Active Release Technique), proprioceptive neuromuscular facilitation stretches, ballistic stretching (BS) and Mulligan traction straight leg raise (TSLR) technique (Avrahami & Potvin, 2014; Halbertsma & Göeken, 1994; Sady, Wortman, & Blanke, 1982; Winters et al., 2004; Yıldırım et al., 2016). Because dynamic and hold-relax proprioceptive neuromuscular facilitation stretches are used as intervention tools in the present study, they are the only techniques that will be covered in the following two subsections.

Proprioceptive neuromuscular facilitation stretching. PNF stretching is considered one of the most popular stretching techniques practiced among clinicians and researchers as it is believed to be superior to static stretching in improving ROM based on its neurophysiological mechanisms mediated by muscle spindles and the Golgi tendon organs (Page, 2012; Youdas et al., 2010). Thus, PNF is based on enhancing proprioception (Sun-Ik et al., 2015), and it can be defined as a combination of passive and isometric contractions of the target muscle or group of muscles. This technique is usually used by therapists to improve muscle flexibility or joint ROM, neuromuscular control and muscular strength (Marek et al., 2005). There are three known techniques for proprioceptive neuromuscular facilitation stretching procedures. These three techniques include contract and relax (CR), hold and relax (HR), and contract-relax with antagonist contraction technique (CR-AC) (Page, 2012; Sun-Ik et al., 2015; Youdas et al., 2010).

The PNF stretching techniques of HR and CR denote the passive placement of the target muscle into a position of stretch, followed by a static contraction and shortening contraction of the target muscle during the HR and CR stretching techniques, respectively (Sharman & Cresswell, 2006). The PNF stretching technique of CR-AC on the other hand, differs than the CR and HR techniques by that static contraction of the target muscle is followed by a shortening contraction of the opposing muscle. This added step is used to place the target muscle into a new position of stretch which leads into an additional passive stretch (Sharman & Cresswell, 2006).

Hold-relax proprioceptive neuromuscular facilitation stretching technique in particular, is widely used by therapists for various therapeutic purposes such as pain and fatigue reduction, increase muscle length, and enhancing stability (Friemert, Bach, Schwarz, Gerngross, & Schmidt, 2006; Malai et al., 2015). HR-PNF is an effective muscle release technique that applies maximum or submaximum (i.e. 75% -100%) resistance during isometric contraction (Friemert et al., 2006; Page, 2012). However, Malai et al., (2015), suggested the use of submaximum voluntary isometric contraction (MVIC ≈25%) while stretching tight iliopsoas muscle in patients with chronic non-specific low back pain and lumbar hyperlordosis.

In a study conducted on 132 patients with bilateral knee osteoarthritis, (Weng et al., 2009) indicated that PNF stretching lead to a greater increase in muscle strength than static stretching following isokinetic muscle strengthen exercises. In a similar study, Malai et al. (2015) reported significant reduction in pain and lumbar lordosis angle, improvement in transverse abdominis activation capacity and iliopsoas muscle length after applying a hold-relax PNF stretching protocol on 20 patients aged 30-35 years with chronic non-specific low back pain with lumbar hyperlordosis ($p<0.05$). However, no significant differences in lumbar stability level was shown as a result of HR-PNF. In another study, Lee, Hwangbo, and Lee (2014) investigated the effect of using PNF pattern and ball exercise in 40 patients with chronic low back pain. Both groups showed significant reductions of visual analogue scale (VAS) over time ($p<0.05$). Additionally, 6 weeks after the intervention, more significant reduction of VAS as well as more increased erector spinae electromyographic (EMG) activity were evident in the PNF combination pattern group as compared to ball exercise group ($p<0.05$).

On the contrary, Bradley, Olsen and Portas (2007) found that PNF stretching decreased muscular performance in a group of 18 of university student (mean=24.3 ±3.2 years). They indicated that vertical jump performance was reduced by a (5.1%) for 15 minutes following a standard cycle warm-up along with PNF stretching ($p<0.05$). Therefore, it is suggested that PNF stretching should not be performed immediately before starting an explosive movement.

Neurophysiological mechanisms related to PNF stretching. There are two neurophysiological mechanisms that underlie the effectiveness of PNF stretch procedures. Those mechanisms are reciprocal inhibition through the muscle spindle and autogenic inhibition via the GTO tension receptor (Chalmers, 2004). The first mechanism, reciprocal inhibition, occurs when a voluntary contraction of the opposing or antagonist muscle (OM) results in decreased activation levels in the target or agonist muscle (TM) (Sharman & Cresswell, 2006; Youdas et al., 2010). During this phenomenon, the same descending signals that activate the motor-neurons within OM, also deliver excitatory input to Ia-inhibitory interneurons which synapse onto TM via its motor-neurons. The inhibition can be further amplified by increased excitatory input arising from Ia-afferents within the OM that join the same Ia-inhibitory interneurons, in particular during contractions with high fusimotor drive. In the PNF stretching literature, increased Ia-afferenet inputs from the opposing muscle is widely reported as a major contributing factor that leads to elongation of the target muscle (Sharman & Cresswell, 2006).

The second mechanism, autogenic inhibition, also known as inverse myotatic reflex denotes the decline in excitability of a stretched or contracting muscle or group of muscles. Reduction of efferent drive to the muscle through autogenic inhibition is a factor believed to contribute elongation of TM, therefore, most PNF stretching procedures incorporate a static contraction of the lengthened TM to benefit from autogenic inhibition phenomenon (Sharman & Cresswell, 2006). However, the role of the GTOs in PNF stretching efficacy is still unclear (Chalmers, 2002). It has been indicated that during PNF stretching, changes in excitability that occur by GTO activity is likely to be limited to the period of tension within the muscle. In two studies, Edin and Vallbo (1990) and Gollhofer, Schöpp, Rapp and Stroinik (1998) demonstrated that following a contraction, the activity of the GTO is either at a very low level or nonexistent. Therefore, it appears that reductions in activity lengthening of TM as well as longer lasting changes in ROM not only induced by autogenic-inhibition but must be as a result of more complex inputs from both central and peripheral neurological entities (Sharman & Cresswell, 2006).

Dynamic stretching. The procedure of dynamic stretching of a muscle or a group of muscles is typically used to increase the dynamic flexibility by contracting the antagonist muscle without bouncing (Yamaguchi & Ishii, 2005). Dynamic stretching is a controlled movement that uses the active ROM of the joint while moving without exceeding extensibility limits of the individual (Fletcher & Jones, 2004).

In recent years, dynamic stretching has been increasingly used by several researchers for different objectives. Those researchers indicated improved high intensity performance in the joint ROM, agility, movement time, dynamic balance, running, sprint, leg power output and jump (Azeem & Sharma, 2014; Chatzopoulos, Galazoulas, Patikas, & Kotzamanidis, 2014;

Fletcher, 2010; Fletcher & Anness, 2007; Little & Williams, 2006; Lucas & Koslow, 1984; McMillian et al., 2006; Shrier, 2004; Thompsen, Kackley, Palumbo, & Faigenbaum, 2007; Yamaguchi & Ishii, 2005; Yamaguchi et al., 2007).

In an older study, Lucas and Koslow (1984) found identical improvements in ROM as a result of using DS and SS). They compared the effects of SS, DS and PNF stretching on hamstring-gastrocnemius muscles' ROM. All three stretches produced significant improvement (p<0.001) in ROM when pre- and post-intervention results were compared and no difference was found between all three stretches condition. Also, another study indicated that dynamic and static stretching procedures were equally effective in improving hip extension ROM in 33 young patients with tight hip flexor tightness (Winters et al., 2004). Regarding the effect of dynamic stretching, Herman and Smith (2008) further indicated the benefits of using dynamic-stretching warm-up intervention on power, speed, agility, endurance, flexibility, and strength performance measures in 24 male collegiate wrestlers when compared to a static-stretching warm-up intervention.

The aforementioned findings, however were questioned by a study investigated acute effects of a general warm-up, SS and DS on hamstrings ROM following assessing passive knee extension test in individuals with previous hamstrings injury and uninjured controls (O'Sullivan, Murray, & Sainsbury, 2009). They reported significant increase in passive knee extension ROM post general warm-up (p<0.001), and further significant increase (p=0.04) after SS, while significant decrease was evident after DS (p=0.013). Despite the significant increase in ROM post general warm-up and SS stretching, ROM decreased significantly (p<0.001) 15-minutes after rest, however it remained significantly greater than the baseline (p<0.001). The results of this study are in disagreement with studies indicating that dynamic stretching is equally effective in improving joint ROM (Herman & Smith, 2008; Lucas & Koslow, 1984; Winters et al., 2004).

Increased muscular power output has been found to be associated with the use of dynamic stretching (Yamaguchi & Ishii, 2005; Yamaguchi et al., 2007). In both of these investigations, the focus was related to leg power output. In Yamaguchi's 2007 study, the DS group showed significantly greater power output than in the non-stretching (NS) group (p<0.05) under 5%, 30%, and 60% of maximum voluntary contractile (MVC) torque with isometric leg extension. The results were (468.4 ± 102.6 W vs. 430.1 ± 73.0 W), (520.4 ± 108.5 W vs. 491.0 ± 93.0 W), (487.1 ± 100.6 W vs. 450.8 ± 83.7 W) under 5%, 30%, and 60% of MVC, respectively. In the 2005 study, Yamaguchi and Ishii measured leg extension power pre- and post-three (DS, SS, and NS) stretches protocol. The results were in agreement with findings mentioned above. Five lower limbs muscle (plantar flexors, hip extensors, hamstrings, hip flexors, and quadriceps femoris) groups underwent DS and SS stretching procedures. DS group was significantly greater than the SS group (2022.3 ± 121.0 W vs. 1788.5 ± 85.7 W) (p<0.01). It is suggested that post-activation potentiation (PAP) caused by voluntary contractions of the antagonist muscle during DS could a possible reason behind increased leg power output in DS group. The latter increase occurred because PAP shortened the time to peak torque and increased the rate of torque development as a result of DS (Yamaguchi & Ishii, 2005; Yamaguchi et al., 2007).

Dynamic stretching has been proven to increase running speed, sprint, agility, and jump performance (Fletcher, 2010; Fletcher & Anness, 2007; Little & Williams, 2006). Little and Williams (2006) indicated that DS produced a significantly (p< 0.005) faster 10-meter sprint acceleration time (1.83 ± 0.08 seconds) compared to NS conditions (1.87 ± 0.09 seconds) and significantly (p< 0.005) faster Zig-zag agility performance (5.14 ± 0.17 seconds) than both SS

(5.20 ± 0.16 seconds) and NS groups (5.22 ± 0.18 seconds). Therefore, Little and Williams suggested that DS is most the effective preparation for subsequent high-speed performance in professional soccer player. In a similar study, significant decrease in sprint time in 50-m sprint activity was reported as a result of dynamic stretching (men p=0.002; women p=0.043) in 18 experienced sprinters (Fletcher & Anness, 2007). In another study, Fletcher (2010) evaluated the effects of different dynamic stretching velocities on jump performance. He stated that faster dynamic stretching velocity of (100 b/min) had a significantly (p<0.001) greater effects on performance of all the three jumps (square jump (SJ), drop jump (DJ), and countermovement jump (CMJ)) than both in the other two conditions (slow velocity of DS (50 b/min) and NS condition). DJ and SJ performance were also significantly (p<0.001) slower in DS than NS condition.

Neurophysiological Mechanisms Related to Dynamic Stretching. In current literature, a number of physiological and neurological mechanisms have been suggested to how dynamic stretching possibly improves muscular performance. These mechanisms PAP (Hough, Ross, & Howatson, 2009), increased muscle and body temperature (Fletcher & Jones, 2004; Yamaguchi & Ishii, 2005), stimulation of the nervous system or improved reciprocal inhibition of the antagonist muscles (Mills et al., 2015; Winters et al., 2004), alteration in musculotendinous unit (MTU) stiffness (Herda et al., 2013) and myotatic or stretch reflex (Gollhofer & Rapp, 1993; Gottlieb & Agarwal, 1979).

Post-activation potentiation is a phenomenon by which the force generated by a muscle is improved due to its previous contraction. In other words, PAP is a theory based on the notion that the contractile history of a muscle affects the mechanical performance of subsequent muscle contractions (Bishop, 2003; Lorenz, 2011; Robbins, 2005). PAP occurs in a situation when a heavier loading is applied to the muscle prior to performing an explosive movement. The latter process may induce further excitation of the CNS leading to an immediate increase in muscle force and rate of force or torque development (RFD or RTD) that occurs as a result of previous activation of the muscle (Mitchell & Sale, 2011; Rixon, Lamont, & Bemben, 2007). Yamaguchi et al. (2007) suggested that PAP was the possible mechanism behind the more rapid or forceful muscle contractions that shortened the time to peak torques and enhanced the RTD following dynamic stretching in 12 healthy male subjects.

Increased muscle and core body temperature as result of dynamic stretching may explain the positive effects of DS technique (Fletcher & Jones, 2004; Yamaguchi & Ishii, 2005). DS activates peripheral blood flow which in turn leads to increases in muscle temperature (Smith, 1994). As a result of the increased temperature, both nerve receptor sensitivity and nerve impulse velocity improve, leading eventually to an enhanced rate of muscle contraction and production of power (Burkett, Phillips, & Ziuraitis, 2005; Faigenbaum et al., 2005; Hamada, Sale, MacDougall, & Tarnopolsky, 2000; Thompsen et al., 2007).

Alteration in MTU stiffness is also suggested to occur as a result of DS (Herda et al., 2013). The MTU include muscles, tendon, and connective tissue. In order to transmit internal muscle forces to the skeletal system, these three types of tissues must contract tightly as a unit (Wilson, Murphy, & Pryor, 1994). To produce a more forceful movement, additional rapid transmission of muscular force to the skeletal system have to occur, and these require a stiffer MTU, increased stiffness in turn leads to advantageous alterations in the force-velocity relationship (Bishop, 2003; Kubo, Kanehisa, & Fukunaga, 2001). Increased compliance of MTU generates lower rate of force transmission during muscle contraction and reduces the capability to store elastic energy. These negative effects of a more compliant MTU results in an increased time for force and signal transmission between CNS and the skeletal system. However, it is worth to mention that these negative changes occur primarily as a result of using static stretching and not dynamic stretching protocols (Fletcher & Jones, 2004; Fowles, Sale, & MacDougall, 2000; Kokkonen, Nelson, & Cornwell, 1998).

Dynamic stretching is proposed to improve the flexibility of the tight muscles while concurrently enhancing the function of the antagonistic muscles (i.e. reducing reciprocal inhibition of the antagonist muscles) (Mills et al., 2015; Winters et al., 2004). The supporters of the Sharman's movement balance system (MBS) procedure states that dynamic stretching improves function of the antagonist muscles. Thus, it creates an equilibrium between the length and function characteristics of the hip flexors and extensors that eventually leads to improved function of the patient and amelioration of tissue trauma. However, this claim needs to be confirmed by further investigation (Winters et al., 2004).

Another proposed mechanism behind the dynamic stretching is the myotatic or stretch reflex. It is defined as a muscle contraction in response to stretching within the muscle. Faster stretching speeds have been found to possibly generate greater action potential of the myotatic reflex (Gollhofer & Rapp, 1993; Gottlieb & Agarwal, 1979). It has been demonstrated that performing dynamic stretching with faster velocity significantly improves take-off velocity and vertical jump performance than slower velocity (Fletcher, 2010).

While the proposed mechanisms mentioned earlier linking dynamic stretching to improved muscular performance offer some answers, it is still necessary to further investigate the effects of dynamic stretching in improving other aspects of fitness such as balance and agility.

Acute Effects of Stretching on Hip ROM

To regain optimum muscle length, stretching is considered to be a crucial component of both sport-related activities and rehabilitation programs (Fasen et al., 2009). It is also extensively accepted in rehabilitation practice that limited hip extension ROM can be reversed by hip flexor stretching (Watt et al., 2011). Stretching have been reported to produce acute changes in joint range of motion (Godges et al., 1989; Halbertsma & Göeken, 1994; Malai et al., 2015; McHugh, Magnusson, Gleim, & Nicholas, 1992; Rodacki et al., 2009; Taylor, Dalton, Seaber, & Garrett, 1990; Willy, Kyle, Moore, & Chleboun, 2001).

A number of theorized mechanisms has been believed to be behind the improvement in muscle flexibility as a result of stretching. Autogenic inhibition and tensile stress applied to the muscles was suggested to be the mechanism responsible for the improvements in patients following static stretching (Tanigawa, 1972). Applying stress over a constant period of time affect the viscoelastic characteristics of the muscle which in turn will induce a gradual relaxation of the muscle. This muscle relaxation results in increase in length of the muscle and ROM of the joint the muscle crosses. Autogenic inhibition on the other hand is explained that after stretching of a muscle, this muscle becomes inhibited, and this inhibition is thought to be accompanied by a simultaneous relaxation, resulting in improved ROM (Winters et al., 2004). However, many studies suggested that autogenic inhibition is not the mechanism responsible for the increase in muscle flexibility, rather, tensile stress is the primary mechanism behind muscle relaxation which leads to any improvement observed following static stretching (Medeiros, Smidt, Burmeister, & Soderberg, 1977; Tanigawa, 1972; Taylor et al., 1990).

As in static stretching, tensile stress is also applied on the muscle during dynamic stretching. Winters et al. (2004) suggested that activating the hip extensors (antagonists) in subjects with tight hip flexors in a shortened range would likely inhibit the hip flexors (agonists) from contracting, allowing them to relax and lengthen. Winters and colleagues proposed that the similar effectiveness of their dynamic and static stretching programs in improving muscle flexibility over time could be explained by the tensile stress mechanism that occurs in both types of stretching (Winters et al., 2004).

In a study conducted on 8 healthy men, hip extension ROM was measured pre- and post-15-minutes of stretching program. Stretching program was designed to stretch six muscle groups of the lower extremities. Improvements in hip extension ROM ranged between 2-6 degrees after a single treatment session. The session consisted of five contract-relax stretches and used 4-6 second contractions of the iliopsoas and rectus femoris muscles, then followed by end-range passive stretches of 8 seconds (Möller, Ekstrand, Oberg, & Gillquist, 1985a).

In another study, Godges et al. (1989) compared SS and soft tissue mobilization with proprioceptive neuromuscular facilitation (STM-PNF) techniques to determine which is most effective for improving hip ROM and gait economy. Significant improvements were reported in hip extension ROM as a result of performing the SS and STM-PNF procedures. The SS, and STM-PNF techniques improved hip extension by 4 and 9 degrees ($p<0.01$), respectively.

Malai et al. (2015) investigated the immediate effect of stretching the iliopsoas muscle using a HR-PNF stretching technique on iliopsoas muscle length and other related variables. Similar to the control group, two males and 8 females (mean=41.70 ± 9.79 years) formed the experimental group. In the experimental group, significant improvements were found in both left and right hip extension ROM post intervention 12.9 ± 9.69 and 10.0 ± 10.43 degrees, respectively ($p<0.05$).

On the contrary, Rodacki et al. (2009) reported nonsignificant improvement (5.7%) in the hip flexion/extension amplitude ($p\leq0.05$) after performing a single session of static stretching exercises for the hip flexor muscle group. This study aimed on evaluating the acute effects of static stretching on gait and several other parameters related to fall risk in 15 healthy women (age=64.5 ±3.2 years).

Acute Effects of Stretching on Balance

In recent years, several studies have investigated the acute effects of stretching on balance. Costa, Graves, Whitehurst and Jacobs (2009) examined the effects of different durations of SS on dynamic balance (DB). Twenty-eight healthy active women (age=18-53 year) were evaluated pre- and post- two stretching interventions and a control condition (CC) on 3 separate occasions, at least 48 hours apart. The SS protocols consisted of a cycle ergometer warm-up at 70 rpm and 70 W followed by SS. Static stretching movement included, supine hip flexion, unilateral knee flexion, ankle dorsiflexion with an extended knee, and ankle dorsiflexion with a semi-flexed knee. Stretching duration were maintained for 15 or 45 second (s) and held 3 times with 15s between stretches. Dynamic balance was measured using a BSS (Biodex Medical Systems) stabilometer. It has been found that the 15s condition significantly improved balance scores by 18.0% ($p=0.004$), while no significant effects were found with CC or 45s condition. Costa et al. concluded that intervention with 15s hold durations may improve balance performance by decreasing postural instability, and that moderate stretching protocol may avoid possibly unfavorable reflex activity decrements. One possible mechanism behind the improved balance performance could be the enhanced proprioceptive feedback that leads in turn to improved JPS. This mechanism was further justified by the findings of a study conducted by (Ghaffarinejad et al., 2007) which indicated improved knee JPS as a result of a single bout of static stretching regimen.

A study by Handrakis et al. (2010) was aimed on assessing the effects of an acute static stretching (SS) protocol on balance and jump/hop performance in 10 active adults (6 men and 4 women aged 40–60 year) recruited from a martial arts school. Biodex Balance System SD was utilized to test DB. Dynamic stability index (DSI) score was used as a dependent variable for single-leg dynamic balance. Smaller DSI meant improved DS while greater DSI indicated the opposite effect. The mean values for balance showed significant difference between the stretch and no-stretch conditions (3.5 6 0.7 vs. 4.3 6 1.4 DSI, respectively; $p<0.05$). No significant differences were found in the other dependent variables between the groups. Thus, it was concluded that using a 30-second hold with 3 repetitions during 1 session of acute static stretching enhances dynamic balance performance in active middle-aged adults. Handrakis et al. suggested that increased performance of DB observed following the stretching protocol could be resulted from improved feedback to the CNS, less stiff muscle-tendon unit and enhanced joint position sense.

In a study conducted on 30 male recreational soccer players (age range=17-25 years), Azeem and Sharma (2014) evaluated the acute effects of DS and SS on DB performance. Ankle planter flexors, quadriceps, hamstring, hip flexors, adductors, and extensors were stretched in this study. DS was performed at a rate of 1 stretch/second (s) for a duration of 30 s for each muscle group. Star excursion balance test was utilized to measure DB. The duration of SS was 15s per muscle group with 15s intervals between sets. Stretching was performed on 3 non-consecutive separate time points within a week. Results showed that both types of stretching significantly improved DB (p<0.001). Azeem and Sharma (2014) suggested that positive effect of SS on DB was possibly due to the improved proprioception and avoidance of undesirable reflex activity decrements. Azeem and his colleague proposed that increased heart rate, core and muscle temperature, improved neural stimulation, specific rehearsal of movement patterns that may enhances proprioception, and increase in neuromuscular activity that possibly linked to PAP were possible mechanisms behind improved dynamic balance performance as a result of using dynamic stretching protocol.

In another study, Chatzopoulos et al. (2014) compared the acute effects of 3 stretching protocols on balance and other variables. Thirty-one female high school athletes (age=17,3 ±0.5 year) performed one of the 3 protocols (SS, DS and NS) on different days. Different upper and lower body muscle groups were stretched. Protocol included 3-minute jogging followed by 7-minute of SS, DS and NS, respectively. Stability platform was used to assess balance. Results indicated that DS and NS protocol compared to SS were significantly better in balance (p<0.05). Balance durations post interventions were (15.34 ±5.54s), (17.49 ±5.11s) and (16.97 ±5.16s) for SS, DS, NS, respectively. Chatzopoulos et al. (2014) stated that better performance of balance in DS compared to SS was possibly as a result of increased muscle temperature, enhanced stimulation of nervous system and electromyographic activity amplitude.

The acute effects HR-PNF and SS stretches on ROM, muscle activation, and balance were investigated in another study (Lim, Nam, & Jung, 2014). Forty-eight male adults (in their 20’s and 30’s) with hamstring muscle tightness randomly and evenly divided into 3 groups: a SS, a HR-PNF stretching groups, and a control group (CG). Force-plate device was used to measure the static balance ability in this study. Despite that both SS and PNF stretching groups showed significant increases in knee extension angle compared to CG (p<0.05), no significant differences were found in either mediolateral or anteroposterior directions of balance test among the groups following the stretching techniques. Nonetheless, postural sway showed a decreasing tendency as a result of both stretching types. Lim et al. purported that the lack of the effect of stretching techniques on balance was because of insufficient frequency and durations of stretching techniques utilized.

In a more recent study, Amiri-Khorasani (2015) examined the effects of static, dynamic, combined (CS=SS and DS) and no stretching or control group on static balance (SB) and DB in 24 healthy female soccer players (age=22.08 ±0.77 year) during warm-ups. SS was held for 15 seconds. Muscle groups stretched included gastrocnemius, hamstrings, hip flexors, extensors, adductors and quadriceps. Stork test was utilized to assess SB, and SEBT was used to measure the DB. DB was improved after DS (1.75±4.01%) compared to SS (–0.063 ±4.38%) (p=0.002), and following CS (2.90±5.41%) compared to SS relative to the CG. No significant difference was found between DS and CS stretching relative to CG (p=0.27). Static balance was improved after DS (1.19 ±3.77 seconds) compared to SS (–1.29 ±2.71 seconds) (p=0.004) and CS (–0.13 ±3.86 seconds (p=0.05) relative to CG. However, no significant difference was reported between SS and CS (p=0.21) relative to CG. Therefore, it was concluded that dynamic stretching had positive effects on both static and dynamic balance performance and suggested to incorporate it in regular warm-up tasks for athletes. The improvement gained using dynamic and combined stretching was supported by the same mechanisms supporting the findings in previous studies (Azeem & Sharma, 2014; Chatzopoulos et al., 2014). However, changing neural factors, such as altered reflex sensitivity or diminished muscle activation were believed to be the mechanism that possibly explains unfavorable effects of SS (Cramer et al., 2004; Nelson, Guillory, Cornwell, & Kokkonen, 2001; Power, Behm, Cahill, Carroll, & Young, 2004).

In summary, adequately flexible muscles and slack connective tissues around the joints following stretching may attribute to the increased joint ROM. Improved dynamic balance as a result of increased flexibility possibly due to the occurrence of desensitization of stretch reflex. Decreased responsiveness of stretch reflex could overpower postural perturbations, enhance the proprioceptive input, which in turn facilitates the attainment of equilibrium. Increased muscle and body temperature might also be contributing factors, which increase nerve conduction velocity. In addition, factors such as specific rehearsal of movement patterns that may enhance proprioception, increased heart rate and stimulation of neuromuscular activity, and improved feedback to the CNS can all contribute to the improvements in dynamic balance performance.

Acute Effects of Stretching on Knee JPS

A number of studies investigated the acute effects of different stretching techniques on knee JPS. In this section, only the studies that specifically examine the acute effects of stretching on knee JPS will be included and discussed.

A study by Larsen et al. (2005) evaluated the acute effect of a SS protocol of quadriceps and hamstrings on knee JPS in 20 healthy subjects (14 female, 6 male, age range=21-31 year). A cross over design with a washout time of 24 hours was used for this investigation. Two electrogoniometers were used to measure knee JPS. The ability to replicate the same position used to estimate JPS for the dominant knee and constant error (difference between target and estimated angle) was used for statistical analysis. Measurements were taken before and immediately after SS protocol (30 second of stretch followed by a 30s of pause, repeated 3 times). Measurements were repeated 3 times in a sitting and a prone position. Results showed no significant differences in CE between stretching and control in both sitting and prone positions, (p=0.99) (0.00; 95% confidence interval 20.98 to 0.99), (p=0.89) (0.12; 95% confidence interval

21.52 to 1.76), respectively. Larsen et al. concluded that the static stretching protocol used had no effect on knee JPS measured in either sitting or prone position in healthy participants. Larsen et al. suggested that this could have occurred because participants were healthy subjects and their mechanoreceptors' function was as good as it could be before the intervention. Larsen et al. also questioned the efficacy of the stretching protocol itself for the lack of its effect on knee JPS.

Similarly, Ghaffarinejad et al. (2007) investigated the effect of SS of the muscles surrounding the knee on knee JPS in healthy students (21 female, 18 male; mean age=25.6 year). JPS was measured through the absolute angular error (AAE) in order to estimate the ability to reach 2 target positions (20° and 45° of flexion) in the dominant knee. Measurement of knee JPS was conducted utilizing electrogoniometer. Each muscle was stretched using three 30 second stating stretching with a 30 second pause. AAE values were measured 3 times before and immediately after SS. Results indicated significant decrease in AAE after stretching the quadriceps (3.5 (1.3) vs 0.7 (2.4); $p<0.001$), hamstring (3.6 (2.2) vs 1.6 (3.1); $p=0.016$), and adductors (3.7 (2.8) vs 1.7 (2.4); $p=0.016$) in 45° of flexion. However, non-significant differences were found for all muscles during 20° of flexion ($p>0.05$). Ghaffarinejad et al. suggested that stretching may increase proprioceptive feedback which indirectly can enhance sensory imagery. Results suggest that improvement in knee JPS at 45° of flexion following SS contributed to knee joint stability. This is also expected to enhance balance performance since JPS is closely related to proprioceptive response.

In a more specific study aimed on stretching only the quadriceps muscle, Torres, Duarte and Cabri (2012) evaluated the acute effect of a bout of static stretching on knee JPS, sense of force and threshold to detect passive movement. This study recruited 30 young, healthy men (age=22.1 ± 2.7 year) and divided them into a stretching group (SG, n=15) performing 10 static stretches of 30 seconds and a (CG, n=15) resting for identical time interval. An isokinetic dynamometer was used to measure the variables of interest in this study. All variables tested showed nonsignificant changes within and between the SG and CG groups ($p>0.05$). Torres and his colleagues concluded that SS of quadriceps had no effect on the knee JPS and other tested variables, suggesting that SS has no noticeable effect on Golgi tendon organs activation and characteristics of muscle spindle firing which could negatively affect joint proprioception.

Another study by Moradi et al. (2014) examined the effect of static stretching of selected muscles (quadriceps, hamstrings and gastrocnemius) around knee on knee JPS in 30 college level soccer players (age=23.20 ±1.45 year). Five-minute warm-up on a stationary bike was performed before stretching exercises and measurements. Electrogoniometer was utilized to measure knee JPS pre- and immediately post SS of the selected muscles. No significant difference was reported in the mean of knee JPS values between pre- and post-intervention measurements ($p=0.13$). Moradi et al. suggested that the nature of inactivity (i.e. no muscle contraction is used to improve flexibility and muscle is stretched by external forces such as gravity or someone else) of SS is probably a reason that affected the results. Nonetheless, researchers concluded that static stretching is safe and could be used by athletes, trainers and coaches without fearing the unfavorable effects of SS on proprioception parameter.

In a more recent investigation, Sun-Ik et al. (2015) studied the effect of a HR-PNF stretching technique on knee JPS in 40 healthy adults (male, female age=20.21 ±1.11year) randomly assigned into the stretching group (n=19) and control group (n=21). HR-PNf technique was repeated 3 times, holding for 7s and relaxing for 5s. Knee JPS was measured at a prone position with knee flexion angle of 30°, 60 °, 90 ° and 120 ° using an isokinetic dynamometer. Results indicated nonsignificant difference in knee JPS between the experimental and control groups (p>0.05). However, significant differences were observed among the mean errors for 30°, 60°, 90° and 120° knee JPS (p>0.05). According to the results, it is demonstrated that HR technique has an effect on knee JPS. Sun-Ik et al. suggested that using a prone position for testing and a supine for stretching may have possibly affected the results.

In general, except for the study conducted by Ghaffarinejad et al. (2007), it appears that all of the studies discussed in this section failed to show statistically significant changes in knee JPS as a result of stretching of the muscle related to the knee joint. This is consistent with the findings of a study that examined the acute effect of stretching on shoulder JPS (Björklund, Djupsjöbacka, & Crenshaw, 2006). Nonsignificant effects were justified by a number of possible reasons which included differences between testing and stretching positions, subjects being young and healthy and the nature of the stretching techniques utilized. However, improved proprioceptive feedback was suggested as a potential mechanism behind the reported improvement in knee JPS.

Summary

Dynamic and PNF stretching techniques are widely used in clinical and athletic training settings. These techniques started to gain even more popularity specifically after recent studies indicating the possible detrimental effects of static and ballistic stretches on athletic performance and the integrity of different body tissues. Tight hip flexor is a common health concern that afflicts all age groups and genders. It is related to low back problems, lower extremity injuries and increased risk of falls. Studies discussed in this chapter indicated significant effects of stretching techniques used on increasing hip extension ROM, static and dynamic balance performance. However, dynamic and PNF stretching techniques showed greater positive effects on these variables as compared to static stretching techniques.

Despite the nonsignificant effects reported in most of the studies investigating primarily the effects of static stretching on knee JPS, they still showed a trend of improvement in JPS performance. Further, as a reliable and valid measure of dynamic balance, performance of dynamic balance assessment using SEBT could be affected by condition such as restricted hip extension ROM, fatigue, balance training, neuromuscular control procedures and other types of interventions. Yet, the acute effects of dynamic and PNF stretching protocols on dynamic balance ability assessed by the SEBT in subjects with tight hip flexors still unclear. Additionally, since mechanoreceptors are sensitive to changes (i.e. tension and length) in muscles and tendons, thus, it is justifiable to suggest that stretching could affect balance and JPS. Studies investigating the acute effects of dynamic stretching on dynamic balance are scarce. Moreover, no research has investigated the effect of PNF and DS on knee JPS and dynamic balance despite their intimate relationship as both being proprioceptive parameters. Determining if these two stretching techniques have positive influence on dynamic balance and knee JPS using reliable and valid measuring protocols will open the road to further studies investigating other joints and populations.

Chapter III

Methods and Procedures

Introduction

This study was designed to examine the acute effects of two hip flexor stretching techniques (hold-relax proprioceptive neuromuscular facilitation, HR-PNF and dynamic stretching (DS) on hip extension range of motion (ROM), knee joint position sense (JPS), and balance (DB). Knee JPS and DB data were collected before and after performing stretching protocols, while data of hip extension ROM was collected at pre, post immediate and post-5-minutes of performing stretching protocols. This chapter describes the subject sample and the design of the study. Experimental procedures that include stretching protocols, data collection procedures relating to instrumentation, and measurement techniques are also discussed here. Then, description of the statistical analysis of the data is presented at the end of this chapter.

Description of the Study Sample

The study sample consisted of thirty-six college age students (24 males, 11 females, age 22.39 ±1.63 y/o) from the department of Health and Human Development at Western Washington University, Bellingham, Washington. Participants were recruited from Western Washington University (WWU) Kinesiology classes and from posted flyers on the WWU campus. A statistical power analysis based on a previous study (Winters et al., 2004) and calculated using G* power 3.1 software (Heinrich Heine University, Düsseldorf, Germany) revealed that 18 participants per group would result in an estimated power of 0.80 to observe significant differences with the alpha level set to 0.05. The primary criterion for inclusion to this study was the presence of hip flexor muscle tightness. Hip flexor muscle tightness in the current study was identified as a subject demonstrating a bilateral hip extension angle between +5 to +15 degrees above the horizontal line during the modified Thomas test. Subjects who reported lower extremity injuries or pain in the past six months were excluded from participating in this study. Subjects with orthopedic, neurological, cardiovascular abnormalities, or surgeries, as well as a history of participating in a proprioceptive or balance training programs in the past 6 months, were also not allowed to participate in this study. The Ethics Committee on Human Subjects of Western Washington University approved this experiment. A written informed consent, health history and physical activity questionnaire forms were provided for all participants prior to data collection.

Design of the Study

A pretest-posttest randomized experimental groups design was used for this study. The current study utilized two treatment groups; group A performed a DS protocol while group B underwent a HR-PNF stretching protocol. Hip extension ROM, knee JPS (constant error, CE) and DB (% distance of reach) were the dependent variables measured pre- and post-stretching (post-immediate and post-5-miutes for hip extension ROM) protocols. Pre- and post-intervention time points, type of stretching technique and side (for hip extension ROM), knee angle (for JPS) and direction (for dynamic balance) were the three independent variables in this study.

Experimental Procedures

Following the submission of the completed, informed consent (Appendix A), health history, and physical activity questionnaire forms (Appendix B), the principal investigator (PI) reviewed all forms for accuracy and potential omissions. The PI and his assistants explained and demonstrated all the tests and interventions (intervention specific to each group) used in this study (i.e. hip extension ROM, dynamic balance, knee JPS and the two stretching protocols) for the participant. All questions from the participants were thoroughly answered by the examiner before initiating the baseline measurements. Dynamic or HR-PNF stretching techniques were used as experimental interventions between the pre- and post-test time points for each subject. These techniques, in addition to the warm-up protocol, are explained in the following three subsections.

Warm-up protocol. Before performing dynamic and HR-PNF stretching interventions**,** participants in both groups performed a general warm-up. Warm up protocol consisted of 5 minutes of light jogging on a treadmill at a comfortable self-selected pace.

Dynamic stretching protocol. Participants in group A dynamically stretched their hip flexor muscles. The subjects were asked to lay on their stomach on a massage table, and a small balance foam pad (5 cm height) was placed under their abdomen. A strap was used to stabilize the hips to the table. Subjects were asked to dynamically stretch their hip flexor muscles by flexing the knee (maintaining≈90° angle) of the target limb and extending the hip (lifting the thigh off the massage table until the stretch sensation was felt) by using the gluteal muscles (Figure 1). Subjects repeated this exercise for 10 times within a 20-seconds period (i.e. elevation=1 second, lowering=1 second), and rested for 10 seconds. This was repeated 6 times for each limb. The total time for the dynamic stretching technique was about 7-8 minutes. The duration and frequency of the dynamic stretching technique followed the guidelines of the American College of Sports Medicine (ACSM, 2014).

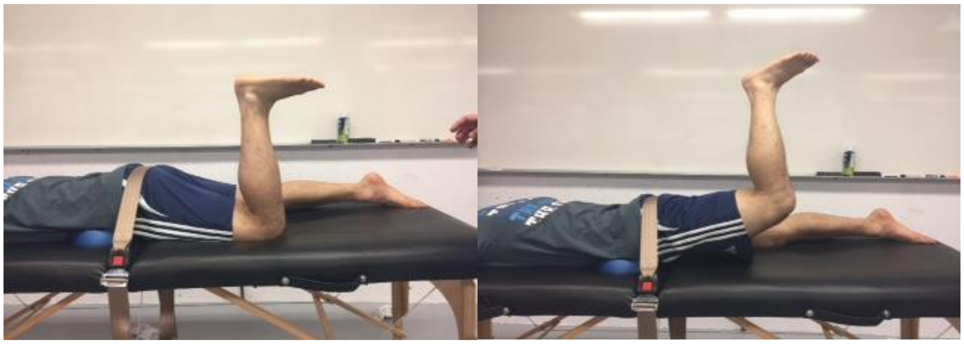

Figure 1. Dynamic stretching technique used for stretching hip flexor muscles.

Hold-relax PNF stretching protocol. In group B, the HR-PNF stretching technique was utilized in the same position as the modified Thomas test describe this. A position that requires subjects lying on their back on a treatment table and holding one knee to the chest and letting the other leg to extend freely toward the floor at the end of the table. (Kendall, McCreary, & Provance, 1993). The HR-PNF protocol used in this study is adapted from a previous study (Malai et al., 2015). The shortened hip flexor muscles in both legs were treated using this technique. The hip of interest was moved gently toward the floor (knee is kept at 90° of flexion) until the participant felt a mild stretch sensation. The subject was asked to perform a sub-maximal voluntary isometric contraction (S-MVIC) of the hip flexor muscles for 10 seconds against a resistance of ≈ 20 lbs. applied using a microFET2, padded hand-held dynamometer (Hoggan Health Industries Inc., Salt Lake City, UT, USA). Then, the leg was slowly moved (gravity + slightly passively by PI) to the new range of motion until a mild stretch sensation was felt and held for 20 seconds (Figure 2). This stretching technique was repeated 6 times for the same limb, then the same steps were performed for the other limb. The total time for the hold-relax stretching technique was about 7-8 minutes.

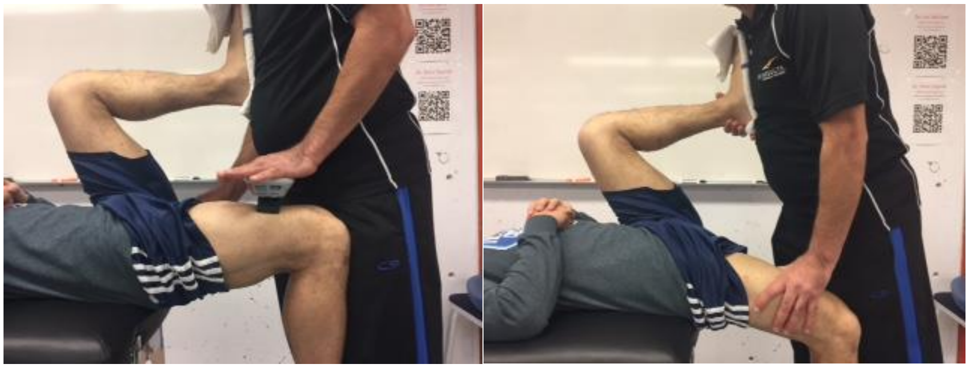

Figure 2. Hold-relax PNF stretching technique used for stretching hip flexor muscles.

After stretching protocols were performed, post-intervention hip extension ROM measures were obtained and followed by measurements of dynamic balance or knee JPS (randomized order), as described below. All testing and intervention procedures were performed in a single session in a controlled research laboratory environment. The duration of a single session was about 45-50 minutes. The same investigator and assistant investigators performed the same tasks throughout the study.

Data Collection Procedures

Instrumentation. A PRO 3600 digital Protractor (Jewell Construction LLC, Manchester, NH, USA) inclinometer and an Apple iPod touch 5th generation device (Apple Inc., Cupertino, CA, USA), integrated with custom-made application software were used to measure hip extension ROM and knee JPS in both experimental groups, respectively. Intra-rater reliability for the hip extension ROM measurements was assessed by a pilot work prior to the initiation of the study in a sample of 10 subjects. An excellent degree of reliability was found between test and retest measurements (ICC<0.96). The same procedures used to assess the reliability of hip extension ROM measurements, were used during the study. The star excursion balance test (SEBT) using the Y-Balance test kit (Perform Better Inc., West Warwick, RI, USA) was utilized to measure the dynamic balance performance. The Y-balance test kit includes 3 lines (wooden rods) that extend to anterior, posterolateral, and posteromedial directions in relation to the stance foot. The length of each side of the Y figure was 144 centimeters (cm). The angle between the arms of Y shape is 90°, and the angle between each arm of the Y shape and its leg is 135°. A rectangular piece of wood (L=49.5cm, W=13cm and H=4.5cm) forms the center of the Y shape kit and the 3 rods attach to this piece in a pin and hole fashion. A smaller rectangular piece of wood (L=25cm, W=13cm and H=4.5cm) with a half-circular groove slides along each of these three rods. The rods are marked with centimeter units to facilitate easy reading of achieved distance of reach. Participants were instructed to stand on the center of the Y figure during testing. The center of the Y shape was marked with a small black to facilitate accurate positioning of the stance foot, (i.e. big toe next to but not touching) (Hertel et al., 2006). Length of legs of the subjects were measured using a tape measure.

Measurement techniques and procedures. Before the initiation of testing the participants, appropriate preparations were assured for hip extension ROM, knee JPS and dynamic balance measurements. A checklist form (Appendix C) was utilized to document the demographic (i.e. age, sex, weight, and height) information of each participant during the baseline measurements. A scale and a stadiometer were utilized to measure the weight and height of the participants, respectively. To achieve the required level of randomization during testing procedures, the order of knee JPS and dynamic balance performance tests was randomized for all subjects to reduce the learning effects. Knee JPS trials were randomized by the custom-made application software integrated to the iPod touch device. Randomization of the order of reach directions in DB test was performed using an online software called Random Number Picker. Numbers of 1, 2, and 3 represented anterior, posteromedial and posterolateral directions of reach, respectively. Accordingly, the software generated 6 randomized orders of reach directions for the 6 trials (3 pre- and 3 post-trials).

Hip extension ROM test. To measure hip flexor tightness (i.e. hip extension ROM) the modified Thomas test was used. The following steps were used during the test: the participants were instructed to sit as close to the edge (i.e. the gluteal folds at the edge) of the table as possible; subjects pulled their knees to their chest and then gently rolled backward on the table; while maintaining this position, one of the lower limbs was released, allowing the hip to extend toward the floor; the free hand was used to help holding the other knee to the chest. This position enabled both the leg and knee of the limb being measured to hang off the edge of the table freely unsupported. While the subject kept a posterior pelvic tilt, the examiner assistant placed one of his hands (four fingers) under the lumbar spine to ensure that the lumbar spine was flat. The examiner observed and palpated the thigh to ensure that it was completely relaxed and positioned the knee joint at about 80-90° of flexion before measuring hip ROM. Then, the examiner placed (slightly pressed) the digital inclinometer on the middle point of the anterior aspect of the thigh being tested (Figure 3). The middle point on the thigh was identified as the midway between trochanterion and the lateral epicondyle of the femur. Values of inclinometer greater than 0° (+) indicate that the thigh was positioned above the horizontal line. In this study, any participant who showed positive inclinometer values (between 5 to 15°) during the modified Thomas test was included and considered as having tight hip flexor muscles. Inclinometer values below 0° (-) indicate that the thigh was below the horizontal line. Any participant who showed inclinometer values below +5° was excluded and considered as not having a tight hip flexor muscles. During the pre- and post-immediate and post-5-minute of intervention time points, hip extension ROM was measured 3 times, and the average value of these 3 trials was used for statistical analysis.

Participants who met the inclusion criteria were measured again after the interventions, and following identical steps to the pre-intervention procedures. All hip extension ROM measurements were taken by the same experimenter to reduce experimental errors.

Figure 3. Hip extension ROM test using a digital inclinometer

Knee JPS test. A 5th generation model PE643LL/A, Apple iPod touch device, integrated with custom-made application software was utilized to measure knee JPS of the dominant knee for all participants. A previous study on knee joint angle replication accuracy demonstrated the validity of this software. The accuracy of the measurements within the iPod touch device was reported to be 0.3° (Lyons et al., 2016). Subjects were instructed to sit comfortably on the treatment table, with their legs hanging off toward the ground. They were barefoot and dressed in shorts and shirt during the test. To avoid cutaneous sensation, a small towel was folded (2.4 cm thick) and placed under the thighs to keep the knee joint and the distal end of the hamstrings free from the edge of the table. The shank was relaxed, and the knees were at a resting position of 90° of flexion. iPod was strapped to the lateral side of the subject's dominant shank about 2.4 cm above the lateral malleolus and secured via a Neoprene sleeve with hook and loop Velcro fasteners (Figure 4). At this point, subjects were asked to close their eyes to ensure elimination of any visual clues. Then, the software instructed the participants to go through various positions of the knee joint angles. Thirty and 60° of knee flexion were used to measure knee JPS in this study. Continuous beeps prompted subjects to extend the knee at the start of each trial. At the moment the knee reached the target flexion angle, the beeps stopped. Then, the participants were told to hold the position for 5 seconds, and they had to concentrate on the knee position during this interval. After holding this position for 5 seconds, an audible sound 'relax' directed subjects to go back to starting position. Then, after being at the starting position for 3 seconds, another beep prompted subjects to try to reproduce the target knee position. A customized LabVIEW (National Instruments Corporation, Austin, TX, USA) was used to calculate the accuracy of the reproduction of each knee joint angle. The accuracy of the reproduction of joint position was represented as a CE. CE refers to the measure of the deviation from the target angle (i.e. overshooting "+" or undershooting "–" the target angle (Vafadar et al., 2015). Participants were given one practice trial to familiarize themselves with the test. Each of the angles was randomly repeated for three times during the pre- and post-interventions tests, the average value of the three trials was then used for statistical analysis. Knee JPS measurements were performed in a quiet room to avoid any external interruptions of the subjects.

Figure 4. Knee JPS measurement using iPod touch device.

Dynamic balance test. The Y-balance version of SEBT, based on Hertel et al. (2006), used to measure dynamic balance performance during pre- and post-interventions measurements for all participants. Subjects were barefoot and wore shorts and shirts during the test. The distal tip of the big toe of the dominant leg was placed next to the small black line located on the center piece of the Y figure. While maintaining a single-leg stance on the stance foot, participant's contralateral leg tried to gently push each of the smaller sliding rectangular pieces as far as possible along each rod. Subjects pushed the rectangular pieces to the farthest point possible on each line with the most distal part of their reaching foot (Figure 5). During pushing these pieces to the farthest point on the line, the push had to be as gentle and as gradual as possible so that the reaching leg did not kick the gliding pieces of wood away and did not considerably contribute in the maintenance of upright posture. If the stability of the base of support was compromised or the reaching foot was used to maintain the upright posture, the trial had to be performed again. The distances reached were immediately recorded after each trial by one research assistants. After the completion of each trail, participants were returned to bilateral stance. The distances of reach from the center of the Y shape to where the small gliding piece had arrived were recorded to the nearest quarter of centimeter. Next, these distances were normalized to the length of subjects' legs (Gribble & Hertel, 2003). Length of leg was identified as the distance from the anterior-superior iliac spine to the medial malleolus of the fibula. To evade sequencing effects on the collected data, the sequence of reach directions was randomized using a computer software. Participants were given 1-2 practice trials to familiarize themselves with the Y-balance test. Then, they were instructed to perform 3 trials in each direction (i.e. anterior, posteromedial and posterolateral) and 15 seconds of rest were given between each trial. The mean value of the 3 trials during the pre-and post-interventions measurements was used for statistical analysis. To eliminate visual and auditory influences during the test, no visual cues, objects on the floor and people in front of the participants were allowed. In addition, no further instruction or encouragement was provided to the subjects during the SEBT (Hertel et al., 2006).

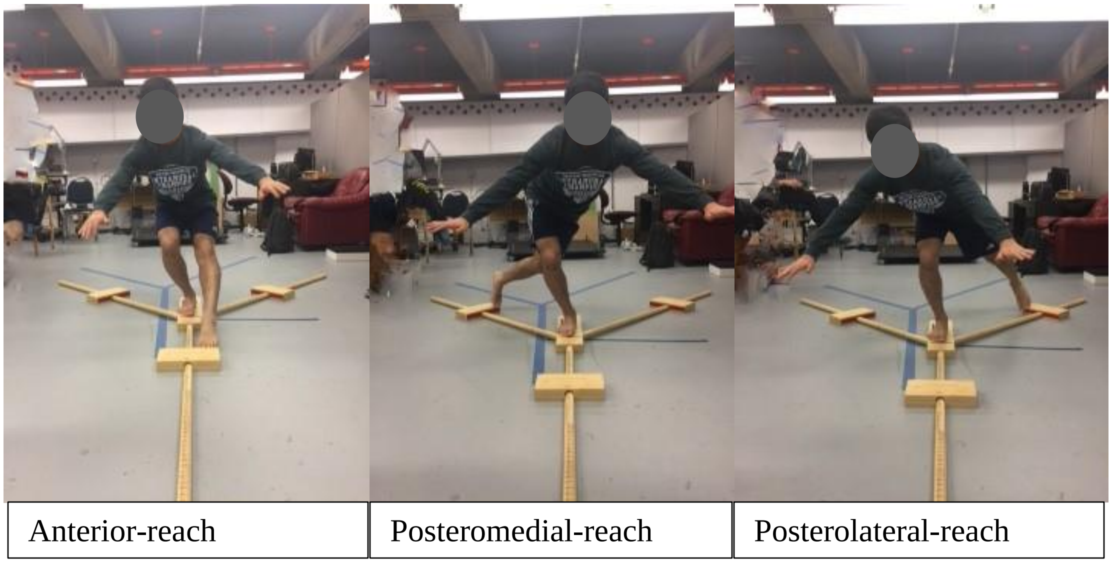

Figure 5. The ‘Y’ configuration of the Star Excursion Balance Test.

Statistical Analysis

Mean and standard deviation values for hip extension ROM, scores of DB performance and knee JPS replication error CE during the pre- and post-intervention time points for both groups were calculated using Microsoft Excel 2013 (Microsoft Inc., Redmond, WA, USA). The effects of time, group and side of hip on hip extension ROM; time, group and knee angle on CE of knee JPS; and time, group and direction of reach on dynamic balance scores were analyzed using a 3-way mixed analysis of variance (ANOVA) with SPSS version 21 (IBM Corp., Armonk, New York, USA). The ANOVA was conducted to compare the group (dynamic stretching vs PNF stretching), time (pre-stretching vs post-stretching), and side of limb (right vs right for hip extension ROM). For the knee JPS, angle (30° vs 60° in knee JPS) was used instead of the side of limb. For the Y-balance test, the direction (anterior vs posteromedial vs posteromedial) substituted the side of limb. If statistical significance with the two-way interaction or main effects existed, then a pairwise comparison performed, and Bonferroni correction was applied. A pairwise comparisons were also performed if statistical significance was evident with the simple effect analysis. Additionally, a partial-eta squared was calculated to determine the effect size. SPSS was also used to calculate Intraclass Correlation Coefficient (ICC) value of hip extension ROM measurements for the pilot study that was conducted prior to the initiation of the research project. Statistical significance was set at an alpha level of 0.05.

Chapter IV

Results and Discussion

Introduction

This study tested the hypothesis that applying dynamic (DS) and hold-relax proprioceptive neuromuscular facilitation (HR-PNF) stretching techniques would result in significant differences in hip extension range of motion (ROM), knee joint position sense (JPS) and dynamic balance (DB) measurements prior to and following the two stretching protocols as well as between the two stretching groups at post intervention time point. Hip extension ROM was measured during three time points (i.e. pre-stretching, post-immediate-stretching, and post-5-minute of stretching). Knee JPS constant error (CE) and dynamic balance (the Y-balance test) were measured during two time points (pre-stretching and post-stretching). Hip extension ROM, knee JPS CE, and the dynamic balance measurements represented the dependent variables in this study. A Three-way mixed analysis of variance (ANOVA) was performed to compare the group (dynamic stretching vs HR-PNF stretching), time (pre-stretching vs post-stretching), and side of limb (right vs right for hip extension ROM). For the knee JPS, angle (30° vs 60° in knee JPS) was considered instead of the side of limb. For the Y-balance test, the direction (anterior vs posteromedial vs posteromedial) replaced the side of limb. If there was statistical significance with the two-way interaction or main effects, a pairwise comparison performed, and Bonferroni correction was applied. Additionally, pairwise comparisons were performed if statistical significance was evident with the simple effect analysis. A partial-eta squared was calculated to determine the effect size that would be attributable to any of the independent variables. A two-tail t-test (two-sample of unequal variance) was used to test if there were significant differences between dynamic and PNF stretching groups during pre-stretching time point in subjects' characteristics and all other dependent variables.

Results

Subject characteristics. Thirty-six subjects (25 males, 11 females), aged 19-27 (22.39 ±1.63) years old, participated as volunteers in this study. Due to equipment malfunction of the JPS measuring device, the data of one of male participant was excluded from statistical analysis. All participating subjects were students at the Western Washington University campus in the department of Health and Human Development, and they were free from any lower back, hip and lower limb injury in the last six months. No significant differences were found between dynamic and PNF stretching groups in subjects' characteristics or any of the independent variables at the pre-stretching time point. Characteristics of subjects and values of two-tailed t-test at the pre-stretching time point in both groups are presented in tables 1 and 2.

Subject Characteristic	Dynamic Stretching Group n=17 (12 males, 5 females)	PNF Stretching Group n=18 (12 males, 6 females)	*P* value
Age (years)	22.71 ± 1.79	22.06 ± 1.47	0.25
Height (cm)	171.01 ± 12.36	171.08 ± 6.50	0.98
Mass (kg)	75.83 ± 15.82	70.30 ± 11.15	0.24
Leg length (cm)	92.10 ± 7.34	91.44 ± 4.28	0.75

Table 1. Subject characteristics mean ± standard deviation (SD).

Dependent variable	Dynamic Stretching Group n=17 (12 males, 5 females)	PNF Stretching Group n=18 (12 males, 6 females)	*P* value
R. hip extension ROM (°)	9.20 ±2.88	9.54 ±2.58	0.72
L. hip extension ROM (°)	8.89 ±2.29	10.34 ±3.28	0.14
Knee JPS CE at 30° (°)	5.99 ±2.43	6.23 ±4.91	0.85
Knee JPS CE at 60° (°)	1.03 ±2.97	2.12 ± 3.28	0.31
Y-test/anterior (%)	64.57 ±6.66	68.30 ±5.27	0.08
Y-test/posteromedial (%)	102.47 ±9.43	105.11 ±11.31	0.46
Y-test/posterolateral (%)	108.90 ±9.36	112.91 ±10.52	0.24

Table 2. Dependent variables' mean ± standard deviation (SD) values at pre-stretching time point. (R=right, L=left, 30° and 60°=knee angles).

Hip extension range of motion. The results of this test supported the hypothesis which stated that there will be significant differences both within and between groups in hip extension ROM after applying dynamic and HR-PNF stretching techniques. Mauchly's test for sphericity revealed that the data for hip extension ROM met the assumption of sphericity for the side of limb and time interaction. Therefore, sphericity was assumed. There was not a significant three-way interaction between side of limb, time and stretch type (F [2, 66] =0. 548, p=0.581, η^2 **p.**= 0.016). Also, there was not a significant two-way interaction between the side of limb and time (F [2,66] =0.264, p=0.769, η^2 **p.**=0.008). There was, however, a significant two-way interaction between the side of limb and stretch type (F [1, 33] =8.154, p=0.007, η^2 **p.**=0.198). A Bonferroni correction was applied, a pairwise comparison revealed a significant difference in hip extension ROM for both the right and the left hips between PNF and dynamic stretching groups with a greater improvement in PNF group compared to dynamic group (p=0.001 and p=0.035, respectively). In addition, significant difference was evident in hip extension ROM between the right and left hip in PNF stretching group with a greater improvement in the right than left (p=0.048).

Also, there was a significant two-way interaction between the time and stretch type (F [2, 66] =20.870, p<0.001, η^2 **p.**=0.387). A Bonferroni correction was applied, a pairwise comparison showed significant differences in hip extension ROM between PNF and dynamic stretching groups during post-immediate and post-5-minute time points indicating a better improvement in PNF compared to dynamic stretching group (p<0.001 and p=0.005, respectively). In PNF stretching group, pairwise comparison revealed the following significant differences in hip extension ROM: post-immediate stretching values were better than pre- stretching values, post-5-minute stretching values were better than pre-stretching values, and post-immediate stretching values were better than post-5-minute stretching values (p<0.001). In dynamic stretching group, pairwise comparison indicated significant differences in hip extension ROM; both post-immediate and post-5-minute stretching values were better than pre-test stretching values (p<0.001). Unlike to what was observed in PNF stretching group, no significant difference was found between post-immediate and post-5-minute stretching values in dynamic stretching group (p=0.828).

Based on Mauchly's test for sphericity, the data of hip extension ROM did violate the assumption of sphericity for the effect of time (p=0.01). Therefore, the Greenhouse-Geisser correction for degrees of freedom was applied for this effect. There was a significant main effect of time on hip extension ROM (F [1.602, 52.859] =125.533, p <0.001, η^2 **p.**=0.792). The total mean values of the same side of hip extension ROM for both stretching groups during post-immediate stretching time point were better than during post 5-minute stretching time point (0.18°, 0.27° vs 1.76°, 1.49°, right and left, respectively), which were better than the values during pre-stretching testing time point (1.75°, 1.49° vs 9.37°, 9.64°, right and left, respectively). Also, there was a significant main effect of stretch type on hip extension ROM (F [1,33] =9.753, p=0.004, η^2 **p.**=0.228). The improvement in hip extension ROM values in group (B) who underwent a HR-PNF stretching protocol was greater than the mean values in group (A) who performed a DS technique (-3.87°, -2.48 ° vs 4.46°, 3.17°) and (-0.90°, -0.26° vs 4.57°, 3.35°) right, left, PNF versus DS group, post-immediate and post-5-minute stretching time points, respectively). Further, the ANOVA indicated no significant effect of side of limb on hip extension ROM (F [1, 33] <.001, p=0.989, η^2 **p.**=0.000). Figure 6 below represents hip extension ROM of right and left sides in dynamic and PNF stretching groups. The figure shows the mean and standard deviation of the mean for the data.

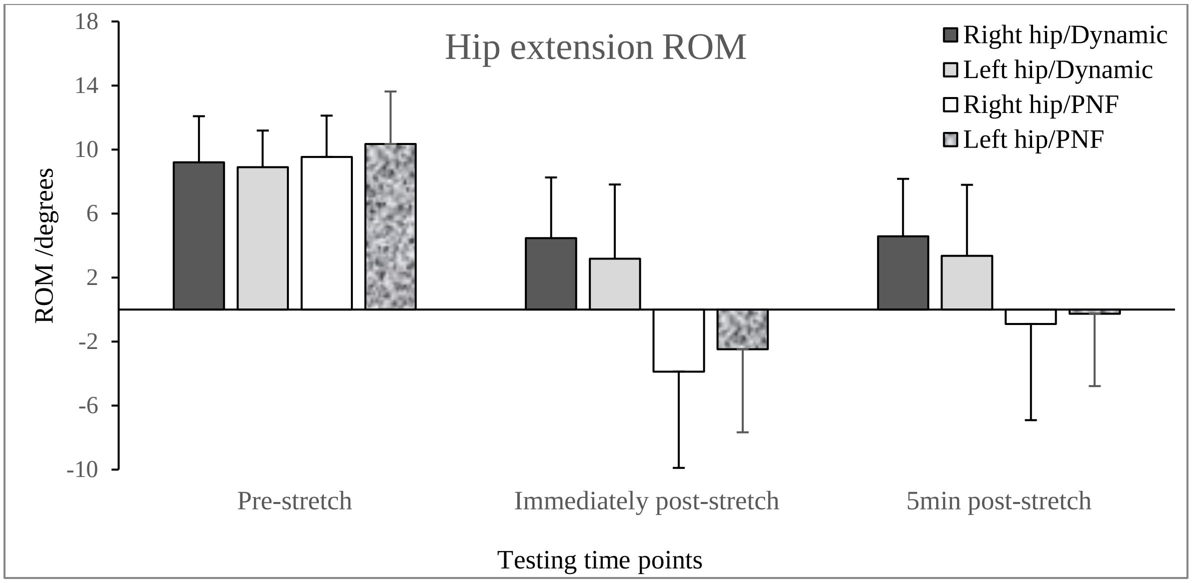

Figure 6. A graphical comparison of hip extension ROM (°) of right and left hips between dynamic and PNF stretching groups during pre-test, immediately post-stretch, and 5-minute post-stretch time points.

Knee joint position sense. The results failed to support the hypothesis for both within and between groups differences in joint replication error CE over time. There was not a significant three-way interaction between time, angle and stretch type (F [1, 33] =0.065, p= 0.801, η^2 **p.**=0.002). Also, there were no two-way significant interactions between time and stretch type (F [1,33] =0.179, p=0.675, η^2 **p.**=0.005), angle and stretch type (F [1, 33] =0.921, p=0.344, η^2 **p.**=0.027), and time and angle (F [1, 33] =3.617, p=0.066, η^2 **p.**=0.099). However, a significant difference was observed between the angles of 30° and 60° over time in joint replication error CE (F [1,33] =51.723, p<0.001, η^2 **p.**=0.610). A Bonferroni correction was applied, and pairwise comparison indicated a significant difference in the mean of joint position replication error CE (i.e. average of pre- and post-combined values in both stretching groups) between the knee angles of 60° and 30° with a smaller error in mean CE (1.90° versus 5.76°) in 60° than 30° of knee angle, respectively (p<0.001). There was not a significant main effect of time on mean joint replication CE (F [1,33] =0.003, p=0.956, η^2 **p.**<0.001). Figure 7 below represents JPS replication error CE at 30° and 60° of knee flexion in dynamic and PNF stretching groups. The figure shows the mean and standard deviation of the mean for the data.

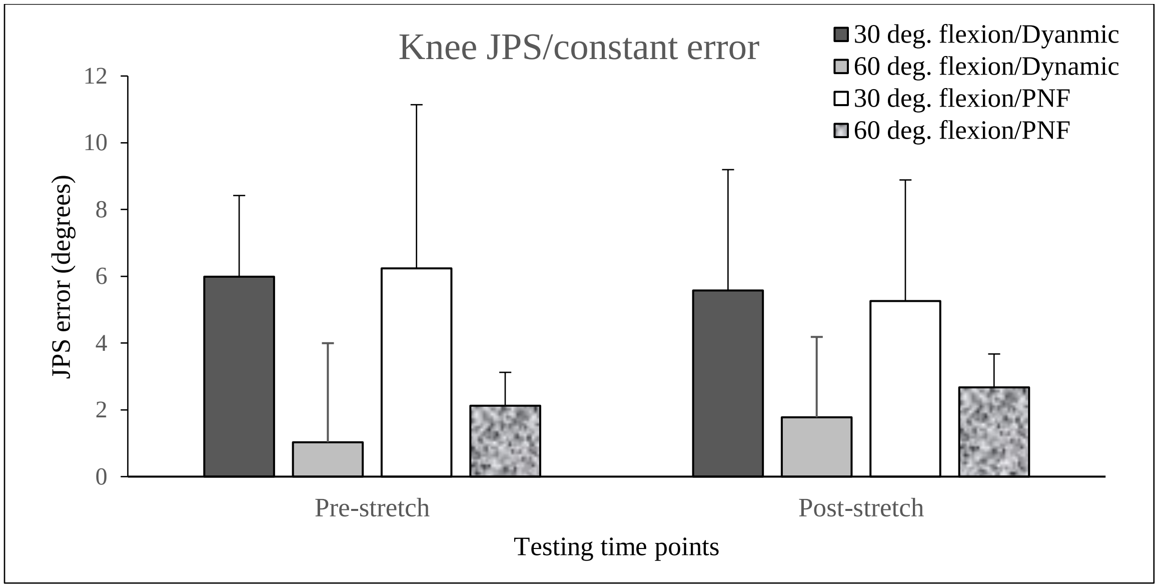

Figure 7. A graphical comparison of knee JPS replication error CE (°) between dynamic and PNF stretching groups during pre-test, post-test time points.

Dynamic balance. The results of dynamic balance (the Y-balance) test partially supported the hypothesis of the study which stated that dynamic and PNF stretching techniques would lead to alterations in dynamic balance performance. Mauchly's test for sphericity revealed that the data for the Y-balance test met the assumption of sphericity for the time and directions of reach interaction. Therefore, sphericity was assumed. There was not a significant three-way interaction between time, directions of reach and stretch type (*F* [2, 66] =1.211, *p*=0.304, η^2 **p.**=0.035). Also, there were no significant two-way interactions between time and stretch type (*F* [1, 33] =3.470, *p*=0.71, η^2 **p.**=0.095), directions and stretch type (*F* [1.564, 51.619] =0.475, *p*=0.578, η^2 **p.**=0.014).

There was, however, a significant interaction between time and directions of reach (*F* [2, 66] =5.653, *p*=0.005, η^2 **p.**=0.146). A Bonferroni correction was applied, and pairwise comparison indicated to a significant difference in distances of reach to posteromedial and posterolateral directions between pre- and post-test results with significantly greater distances during post-test compared to during pre-test time point ($p<0.001$). Also, during pre-test and post time points in both stretching groups, the distance of reach to posterolateral direction was significantly greater than the reach to posteromedial direction which was in turn significantly greater than the reach to anterior direction in both groups ($p<0.001$).

Mauchly's test for sphericity indicated that the data of the Y-balance test did violate the assumption of sphericity for the effect of directions of reach. Therefore, the Greenhouse-Geisser correction for degrees of freedom was applied for this effect. There was a significant main effect of directions of reach on the Y-balance test values (F [1.564, 51.619] =904.148, $p<0.001$, η^2 **p.**=0.965). The total mean distance of reach to posterolateral direction for both stretching groups (pre=110.96 %, post=113.48 %) was larger than the total mean distance of reach to posteromedial direction (pre = 103.82 %, post = 107.94 %) which was in turn larger than the total mean distance of reach to the anterior direction (pre=66.49 %, post=65.64 %) (Figure 8). There was also a significant main effect of time on the Y-balance test's mean distance (F [1, 33] =28.386, $p<0.001$, η^2 **p.**=0.462) with a greater mean distance of reach during post stretching time point than during pre-stretching time point ($p<0.001$). Figure 8 below represents the directions of reach during performing the Y-balance test in dynamic and PNF stretching groups. The figure show the mean and standard deviation of the mean for the data.

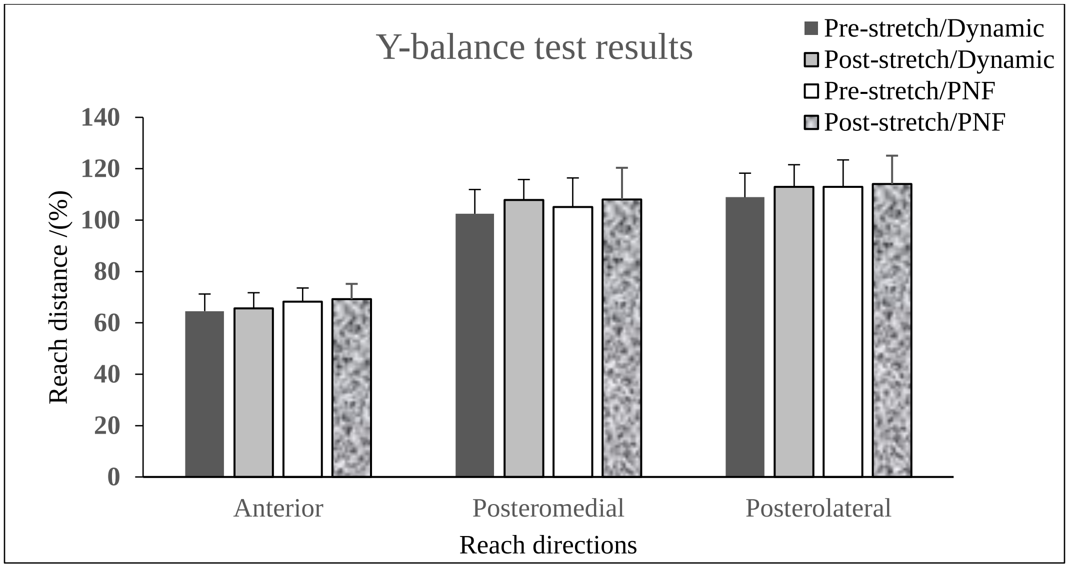

Figure 8. A graphical comparison of the Y-balance test's directions of reach (%) between dynamic and PNF stretching groups during pre-test, post-test time points.

Discussion

The purpose of this study was to investigate the acute effects of two hip flexor stretching techniques (dynamic and HR-PNF) on hip extension ROM, knee JPS and dynamic balance performance. This study consisted of two experimental groups: Group A (n=17) performed dynamic stretching and group B (n=18) underwent HR-PNF stretching technique. Hip extension ROM, knee JPS replication error CE and dynamic balance performance were measured pre- and post-stretching. This study tested the hypothesis that applying dynamic and HR-PNF stretching techniques would result in significant differences in hip extension ROM, knee JPS and DB measurements prior to and following the two stretching protocols. Further, the current study tested the hypothesis that these two stretching techniques would lead to significant differences in hip extension ROM, knee JPS and DB measurements at post-intervention time point between the two stretching groups. Based on the results attained from this study, our hypothesis was generally supported.

Hip extension ROM. The modified Thomas test using a digital inclinometer was utilized to test hip extension ROM during three time points (pre-, post-immediate and post-5-minute of stretching). Results showed significant improvement in hip extension ROM over time in both stretching groups. Hip extension ROM during post-immediate stretch of both groups was significantly greater than hip extension ROM during pre- and post-5-minute stretch measurement. The improvement shown in hip extension ROM in both groups is in agreement with results reported in many similar studies (Godges et al., 1989; Halbertsma & Göeken, 1994; Malai et al., 2015; McHugh et al., 1992; Möller, Ekstrand, Oberg, & Gillquist, 1985b; Taylor et al., 1990; Willy et al., 2001; Winters et al., 2004). Several possible reasons could have led to the improvement seen in hip extension ROM in both stretching groups such as increased body and muscle temperature and stimulation of nervous system (Fletcher & Jones, 2004; Yamaguchi & Ishii, 2005), improved reciprocal inhibition of the antagonist muscles and autogenic inhibition (Mills et al., 2015; Sharman & Cresswell, 2006; Winters et al., 2004; Youdas et al., 2010), alteration in stiffness of musculotendinous unit (MTU) (Herda et al., 2013), alteration in myotatic or stretch reflex (Gollhofer & Rapp, 1993; Gottlieb & Agarwal, 1979).

In agreement with results of the current study, Malai et al. (2015) reported significant improvements in right and left hip extension ROM post stretching using a HR-PNF technique on 10 participants Further, a study also indicated that dynamic and static stretching procedures were equally effective in improving hip extension ROM in 33 young participants with hip flexor tightness (Winters et al., 2004). In another study, Godges et al. (1989) also indicated significant improvement in hip extension ROM as a result of performing static stretching (SS) and soft tissue mobilization with proprioceptive neuromuscular facilitation (STM-PNF) However, Rodacki et al. (2009) reported nonsignificant improvement in hip flexion/extension amplitude after performing post SS for the hip flexor muscles among 15 healthy (age: 64.5 ±3.2 years) female subjects .

The values of hip extension ROM at post-immediate and post-5-minute of stretching in HR-PNF group was significantly greater than in dynamic stretching group. Further, results of HR-PNF stretching group (right and left hips) were significantly greater than dynamic stretching group. It has been reported in the literature that PNF stretching technique is considered as the most effective stretching technique to produce an immediate and short-term increase in ROM (Sharman & Cresswell, 2006). The superiority of this technique may be explained by the inclusion of isometric resistance (hold) phase and followed by a static stretching phase in HR-PNF (Sharman & Cresswell, 2006). These two phases make it a very effective muscle release technique as compared to other stretching techniques such as dynamic stretching (Friemert et al., 2006; Page, 2012). Results of a study conducted by Miyahara, Naito, Ogura, Katamoto, and Aoki (2013) were in agreement with the findings of the current study. Miyahara et al. compared the effects of PNF and SS on maximal voluntary contraction (MVC) in male university students. Researchers reported that PNF stretching technique increased hip flexion ROM significantly greater than SS.

With regard to the significantly greater improvement noticed in hip extension ROM of right side compared to left in HR-PNF stretching group, it is difficult to speculate what may have led to this difference between the sides of hip. A possible factor that could have contributed to this outcome is that the dominant leg for all the 18 subjects in HR-PNF was the right leg. It appears that the dominant and non-dominant sides may have responded differently to this stretching technique due to some potential differences between these sides. A study conducted by Chiu et al. (2016) on 20 healthy subjects (13 males, 7 females) showed that stiffness of non-dominant leg's Achilles tendon (AT) increased significantly after performing 5-mintue of static stretching while the increase did not reach significance level in AT stiffness of dominant side .

The significant differences observed in PNF stretching group which stated that post-immediate stretching values were significantly greater than pre- and post-5-minute stretching values, and post-5-minute stretching values were significantly greater than pre-stretching values can be explained by the nature and duration of effects of PNF stretching technique. PNF stretch is a very effective technique for inducing an immediate and short-term increase of ROM (Sharman & Cresswell, 2006). Therefore, differences were evident among these testing time points. Post-5-minute of stretching, the effect of PNF technique started to diminish over time, thus, significant difference also noticed between immediate and post-5-minute testing time points. On the contrary, in dynamic stretching group, only post-immediate and post-5-minute stretching values were significantly greater than pre-test stretching values. This indicates that even though DS was not as effective as PNF stretching on increasing hip extension ROM, nonetheless, its effect lasted longer and did not diminish as quickly as it occurred in PNF stretching technique.

Knee JPS. Joint position sense was evaluated by knee joint angle replication error at 30° and 60° of knee flexion at pre- and post-stretching time points. The results did not show a significant improvement over time in either experimental group. Also, there was not a significant difference in JPS replication error between the two groups at the post-stretching time point. However, a significant difference in CE between the angles of 60° and 30° was noticed with a smaller replication error in 60° compared to 30° of knee angle. The smaller CE at 60° of knee angle may have occurred as a result of that 60° of knee flexion is closer to a resting position of the knee while sitting (i.e.≈90°), therefore, the body is more familiar with replicating this position as compared to the 30° JPS of the knee. In a study conducted by Erden (2009), he stated that the closer the knee comes to a 90° of flexion, the better the knee JPS gets, however, the results of the same study indicate that the highest error of knee JPS was observed at 60° of knee flexion. Erden compared knee JPS error at 15°, 30°, 60° and 90° of knee flexion.

A possible reason behind the nonsignificant differences noticed in the current study maybe because the participants were young, healthy and physically active individuals. Another probable mechanism that could explain the results of this study could be because these two stretching techniques did not impose adequate effect on the mechanoreceptors in all acting muscle groups around the knee (i.e. stretched only iliopsoas and rectus femoris muscles). Lastly, large values of standard deviations for this measurement may have led to this nonsignificant differences seen within and between the two groups. The findings of this study are in agreement with what have been reported in a number of other similar studies. A study conducted by Larsen et al. (2005) reported no differences in knee JPS after stretching both quadriceps and hamstring muscles of the dominant knee. Larsen et al. proposed that having healthy participants with a good mechanoreceptors' function before the intervention as well as the efficacy of stretching protocol could lead to the nonsignificant differences. Further, Torres et al. (2012) showed that an acute bout of static stretching of quadriceps muscle had no effect on knee JPS. Torres and his colleagues suggested that the lack of effects of an acute stretching bout on knee JPS was possibly due to that stretching may does not have a considerable effect on muscle spindle firing characteristics and Golgi tendon organs' activation. In another study, Moradi et al. (2014) reported nonsignificant difference in the mean of knee JPS between pre and post-tests. Moradi et al. statically stretched quadriceps, hamstrings and gastrocnemius muscles. Moradi and his colleagues suggested the nature of static stretching (i.e. no active muscle contraction) may explain their nonsignificant results. A study conducted by Sun-Ik et al. (2015) using HR-PNF stretching technique and measuring similar angles of knee JPS measured in the current study revealed nonsignificant differences between the control and experimental groups. However, same researchers observed significant differences among the mean errors of 30°, 60°, 90° and 120° of knee JPS. Sun-IK et al. proposed that testing and stretching positions' variation may have possibly affected the results. The results of the current study are also consistent with the findings of another study done by Björklund et al. (2006) who reported no effect of a bout of static stretching (passive) of the agonist and antagonist muscles of shoulder complex on shoulder JPS.

Contrary to the findings of the studies that were in agreement with the findings of the current study, Ghaffarinejad et al. (2007) reported a significant decrease in knee JPS absolute error (AE) after static stretching of quadriceps, hamstrings and hip adductors at 40° of knee flexion. However, there was not a significant difference between pre- and post-stretching AE values of knee JPS at 20° of knee angle. Ghaffarinejad et al. suggested that stretching may have improved knee JPS by increasing proprioceptive feedback which may indirectly cause an enhancement in sensory imagery.

Dynamic balance. The results of Y-balance test generally indicated that both dynamic and HR-PNF stretching groups significantly increased distances of reach over time. There were significant differences in distances of reach to both posteromedial and posterolateral directions between pre- and post-stretching time points. Also, the distance of reach during pre- and post-stretching time points to posterolateral direction was significantly greater than the reach to posteromedial direction which was in turn greater than the reach to anterior direction. There was no significant difference between the two stretching groups in all directions of reach. Improved dynamic balance performance may have occurred due to enhanced proprioceptive feedback to the stretched muscle groups (Ghaffarinejad et al., 2007). Another possible mechanism that may have led to this improvement in dynamic balance performance could be that stretching may have decreased the postural instability in those individuals (Costa et al., 2009). However, the current study did not indicate any significant improvement in knee JPS replication error as a result of applying of either stretching technique. It is also possible that the hold duration during HR-PNF stretching technique and duration of one set during dynamic stretching technique (i.e. 20s in both stretching techniques) was appropriate to produce this significant improvement. This is consistent with what Costa et al. (2009) reported in their study which indicated that static stretching holding for 15s significantly improved dynamic balance scores tested by a stabilometer (Biodex Medical Systems) by 18.0% (p=0.004), while holding for 45s condition did not show any significant improvement. Therefore, moderate hold duration during stretching (i.e. 15-20s) may decrease the possible unfavorable reflex activity decrements (Costa et al., 2009). Improved DB performance could be occurred because of possible enhancement in feedback to the central nervous system, less stiff muscle-tendon unit, increased heart rate and core muscle temperature and improved neural stimulation, however, these variables were not evaluated in the current study.

The findings of the current research are in agreement with the findings of several other similar studies. Handrakis et al. (2010) reported significant difference between static stretching and non-stretching group in dynamic stability index scores in 10 middle aged adults (p<0.05). In another study, Azeem and Sharma (2014), reported significant improvement in DB performance measured by Start Excursion Balance Test (SEBT) after using dynamic and static stretching for several lower limb muscles on 30 male recreational soccer players (p<0.001). The findings of

Chatzopoulos et al. (2014) also indicated that dynamic and no stretching groups were significantly better static stretching groups in balance performance measured by stability platform in 31 female high school athletes ($p<0.05$). The results of a study conducted by Amiri-Khorasani (2015) were also in agreement with our findings regarding dynamic balance performance. He reported that dynamic balance was improved significantly after dynamic and combined stretching (combined=SS and DS) compared to static stretching ($p=0.002$). The results of the last two studies regarding SS effects on DB appear to be in disagreement with the results reported by Azeem and Sharma (2014). Contrary to our findings in the current study, the results of Lim et al. (2014) showed no significant differences among SS, HR-PNF and no stretching groups in the mediolateral and anteroposterior directions of balance test ($p<0.05$). Lim et al. suggested that lack of effects of their program may resulted from insufficient frequency and durations of stretching techniques utilized.

The significant improvement noticed in distances of reach to posteromedial (PM) and posterolateral (PL) directions after stretching in both groups may be explained by the factor of the nature of reach to these directions. These two directions of reach possibly benefited more from stretching of muscles that would directly affect the factor of how far the hip can be extended during the Y-balance test. It is a fact that the stretched muscles (i.e. iliopsoas and rectus femoris) are located on the anterior parts of the hips and legs (Marieb & Hoehn, 2010). Therefore, more flexible muscles in these parts of the body would in turn facilitate greater ability to reach to posterolateral direction first and posteromedial second. During PL reach, the leg is freely reaching away from the body and benefiting greatly from improved ROM of the stretched muscles. During PM reach, the reaching leg still benefits from the gained ROM to reach farther, however, the stance leg is in the direction of reach which in turn restricts how far the leg can reach. Further, since concentric action of hip flexors produce hip flexion and external rotation (Marieb & Hoehn, 2010), these muscles are stretched by hip extension and internal rotation movements (i.e. movements occurred during PNF and DS in this study). Thus, during PL reach, achieving the farthest distance incorporates extension and internal rotation of the hip. This also explains the greater improvement noticed in reaches to PL first, and PM second.

On the other hand, reaching to the anterior direction would not be benefitted from stretching these muscles because the reach to anterior direction does not require the hips to be in an extended position but in a flexed position instead (Figure 5). Additionally, the hip and knee of stance leg is flexed while the free leg is performing the reach, this makes both hips fall behind the stance knee (to maintain balance) which practically limits the reach distance to anterior direction. Another possible explanation for the significant improvement in these two directions could be because of a decreased reciprocal inhibition of the gluteus maximus. It is theorized that shortened and restricted hip flexors may decrease neural drive to hip extensors (i.e. reciprocal inhibition of the gluteus maximus muscle) (Mills et al., 2015). Improved function of this muscle post stretching may be a possible reason for a greater distance of reach (i.e. the reaching leg) to these directions since it is a major thigh extensor. Further, gluteus maximus contributes to maintaining balance of the body because it is a powerful muscle and most effective when the thigh is flexed (i.e. position of stance leg while reaching) (Marieb & Hoehn, 2010). The significant differences observed during the pre- and post-stretching time points between distances of reach to these three directions could be possibly explained by the relationship between hip joint anatomy, ROM of hip, nature of the Y-balance test and directions of reach. This thought is supported by the fact that significant differences between these directions did not change and remained over time during the post-stretching time point too.

Summary

According to the results of this study, the acute effects of using dynamic and HR-PNF stretching techniques on hip extension ROM, knee JPS and dynamic balance varied noticeably. Hip extension ROM improved significantly over time in both stretching groups. Also, in HR-PNF group, hip extension ROM at post-stretching time points (right & left hips) were significantly greater than in DS group. Further, in HR-PNF group, right hip improved significantly greater than left hip, and hip extension ROM values at all 3 time points were significantly different than each other (post-immediate > post-5-minute > pre-stretching). In DS group, however, only post-immediate and post-5-minute stretching values were significantly greater than pre-test stretching values. Several possible mechanisms such as increased body and muscle temperature and stimulation of NS, improved reciprocal inhibition of the antagonist muscles and autogenic inhibition, decreased stiffness of MTU, alteration in myotatic reflex, the nature and duration of effects of PNF and dynamic stretching techniques, all could have contributed to the results seen in hip extension ROM test.

Replication error of knee JPS test results indicated no significant effects of DS and HR-PNF. The lack of significant effect may have occurred as a result of participants being young, healthy and physically active regardless of having tight hip flexors. Also, because stretching did not include all acting muscle groups around the knee.

The results of Y-balance test showed that both stretching groups significantly increased distances of reach over time. Also, distance of reach at both time points to posterolateral direction was significantly greater than posteromedial which was in turn greater than distance reach to anterior direction. Possible reasons behind improvements noticed here could be attributed to decreased postural instability, enhancement in feedback to the central nervous system, less stiff muscle-tendon unit, increased heart rate and core muscle temperature and improved neural stimulation, anatomy of hip joint and nature of Y-balance test. Despite the nonsignificant differences observed in knee JPS replication error and some aspects of dynamic balance measurement, this study demonstrated the benefits of both types of stretching techniques on hip extension ROM and aspects of dynamic balance performance. Nonetheless, further investigation is warranted to understand the mechanisms related to these variables and the use of several stretching techniques to improve them.

Chapter V

Summary, Conclusions, and Recommendations

Summary

Tightness of hip flexor muscles has been recognized as a risk factor for a number of musculoskeletal injuries (e.g., knee and hamstrings) in the lower extremities (Chumanov et al., 2012; Delp et al., 1999; Gabbe et al., 2006; Kolber & Fiebert, 2005; Krivickas & Feinberg, 1996; Zeller et al., 2003). **S**tretching of hip flexor muscles has been acknowledged as effective in reversing limited hip extension range of motion (ROM) (Watt et al., 2011; Winters et al., 2004). Hold-relax proprioceptive neuromuscular facilitation (HR-PNF) and dynamic stretching (DS) techniques have been proven to address this impairment (Malai et al., 2015; Winters et al., 2004). Stretching has also been widely used and recognized to improve abdominal muscle activation, low back pain, lumbar lordosis angle, knee joint position sense (JPS), balance and coordination (Azeem & Sharma, 2014; Ghaffarinejad et al., 2007; Godges et al., 1993; Malai et al., 2015; Pasanen et al., 2009)).

This study investigated the acute effects of dynamic and HR-PNF stretching techniques on hip extension ROM, knee JPS and dynamic balance (DB) performance in healthy subjects who presented with tightness of hip flexor muscles. Results showed statistically significant differences within and between groups in most aspects of hip extension ROM measures and in some aspects of DB measures within groups. Knee JPS replication error showed no significant differences neither within nor between the two stretching groups except the significant difference noticed over time between the angles of 30° and 60° of knee flexion.

Conclusions

Tightness of hip flexors may negatively affect dynamic balance performance but not knee JPS replication accuracy among female and male college age students. Performing a single session of dynamic and HR-PNF stretching protocols could improve hip extension ROM, dynamic balance performance but not knee JPS replication accuracy. Further research is needed to understand how different types of stretching protocols can affect the variables studied in the current study.

Recommendations

Acute effects of different types of stretching techniques on hip extension of ROM, balance and knee JPS have been investigated by a number of previous studies (Azeem & Sharma, 2014; Ghaffarinejad et al., 2007; Malai et al., 2015; Winters et al., 2004). However, to our knowledge, no studies have been conducted to evaluate acute effects of some of stretching techniques on knee JPS and dynamic balance performance in individuals who exhibit hip flexor tightness. Gaining further knowledge about how some of the commonly practiced stretching techniques acutely affect knee JPS and dynamic balance in individuals with tight hip flexors can help in deciding the most effective stretching technique to use in rehabilitation settings.

According to the findings in this study, dynamic and HR-PNF stretching techniques may be used in improving hip extension ROM, and DB performance in rehabilitation settings. These techniques are safe to be used on individuals who suffer from tight hip flexors. Future studies should use more than these two stretching techniques and compare their effects on the same or more variables such as electromyographic readings of the stretched muscles. Additionally, response to different types of stretching techniques could be compared between male and female groups. Further, it would be beneficial to increase the number of subjects and/or test middle aged groups too to see if their response would differ than the current study. Also, testing hip JPS or using several knee angles can also be utilized to investigate stretching effects on knee or hip JPS replication error among subjects with tight hip flexors. This is specifically important because the current study showed no significant difference in knee JPS replication error after using these two stretching techniques. It is also logical in future studies to consider testing flexibility of iliotibial (IT) band in addition to hip extension ROM because it is not uncommon to find individuals who have tightness both in hip flexors and IT band.

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Appendices

Appendix: A

Human Subjects Activity Review

1. **What is your research question, or the specific hypothesis?**

The purpose of this study is to investigate the acute effects of two hip flexor stretching techniques (i.e. dynamic (DS) and hold-relax proprioceptive neuromuscular facilitation (HR-PNF)) on hip extension range of motion (ROM, the movement of a joint from full flexion to full extension), knee joint position sense (JPS, the sense of the static position of a joint) and dynamic balance performance in healthy college age students who exhibit hip flexor tightness. Further, we want to determine which one of these techniques has a greater influence on hip extension ROM, knee JPS and dynamic balance performance. Our experimental hypotheses state that: there will be significant differences in hip extension ROM, knee JPS and dynamic balance measurements prior to and following the two stretching protocols. Also, there will be significant differences in hip extension ROM, knee JPS and dynamic balance measurements at post intervention time point between the two stretching groups.

2. **What are the potential benefits of the proposed research to the field?**

The novel insight that the current study will provide about the effects of these two stretching techniques on hip extension ROM, knee JPS and dynamic balance performance is very important. Thus, gaining a better understanding of the stretching techniques would lead to possible adaptation in improving health and fitness aspects in both athlete and non-athlete alike. Restricted or tightness of hip flexor muscles has been acknowledged as a risk factor for various lower extremity musculoskeletal injuries [1–8]. However, this tightness is proven to be improved by stretching the hip flexor muscles [7,9]. Dynamic stretching incorporates a concomitant active contraction of antagonist muscles. Therefore, and due to its distinct benefits on muscular performance, DS has been increasingly suggested as superior stretching technique [10–12]. Proprioceptive neuromuscular facilitation stretching on the other hand, is considered one of the most effective stretching techniques used to improve ROM, particularly in respect to short-term changes in ROM [13,14]. Therefore, using the more effective stretching techniques may lead into a greater health benefits than using other stretching techniques. Studies which investigated the acute effects of dynamic stretching on dynamic balance and knee JPS are scarce to our knowledge. Moreover, no research has investigated the effects of a widely used dynamic and PNF stretching techniques on knee JPS and dynamic balance despite the close relationship between them as both involves proprioceptive parameters. Based on the results of this study, the acute effects of these two stretching techniques on dynamic balance and knee JPS in healthy college age student population will be determined.

3. **What are the potential benefits, if any, of the proposed research to the subjects?**

Potential benefits of this investigation to the participating subjects may be reflected as improved hip extension ROM, improved posture, enhanced balance and knee joint position sense.

4. **Answer a), then answer either b) or c) as appropriate.**
    a. **Describe how you will identify the subject population, and how you will contact key individuals who will allow you access to that subject population or database.**

Subjects will be recruited within the department of Health and Human Development (HHD) and from other colleges within the campus of Western Washington University.

   b. **Describe how you will recruit a sample from your subject population, including possible use of compensation, and the number of subjects to be recruited.**

The population of this investigation will include 36 healthy male and female subjects (18-28 years old) who will be recruited from the department of HHD and other colleges within the campus of Western Washington University. The subjects will be included in this study only if they present with tight hip flexors (i.e. hip extension ROM measure = +5 to +15 degrees above the horizontal line during the modified Thomas test), and no history of lower back, hips and lower extremity injuries or disorders within the past six months. If the participant could not complete any steps of testing or intervention, they will be excluded from the study. There will be no compensation as a result of participation in this investigation. However, extra credit will be offered to students enrolled in classes that will allow it.

5. **Briefly describe the research methodology. Attach copies of all test instruments /questionnaires that will be used. Note: All attachments must be in final form; drafts are unacceptable.**

Experimental Procedures

Completed informed consent (Appendix A), health history, and physical activity questionnaire forms (Appendix B) (see attached forms), will be reviewed for accuracy and potential omissions by the principal investigator (PI). Dynamic and hold-relax PNF stretching techniques will be used as experimental interventions between the pre- and post-test. Participant in both groups will perform a general warm-up consisting of 5 minutes of light jogging on a treadmill at a comfortable self-selected pace before dynamic and HR-PNF stretching interventions.

Dynamic stretching protocol. Participants in group A will lay on their stomach on a massage table and dynamically stretch their hip flexor muscles by flexing the knee (≈ 90° angle) of the target limb and extending the hip until the stretch sensation is felt. Subjects will repeat this exercise for 10 times within a 20-seconds period, and rest for 10 seconds. This will be repeated 6 times for each limb. The total stretching time will be about 7-8 minutes[15].

Hold-relax PNF stretching protocol. In group B, the HR-PNF stretching technique will be utilized in the same position as the modified Thomas test[16]. Both hips will be stretched using this technique. The thigh will be moved gently toward the floor until a mild stretch sensation is felt. Then, the subject will be asked to perform a sub-maximal voluntary isometric contraction (S-MVIC) of the hip flexor muscles for 10 seconds against a hand-held dynamometer. Next, the leg will be slowly moved to the new ROM until a mild stretch sensation is felt and held for 20 seconds. The stretching will be repeated 6 times for each limb. The total time of this stretching technique will be about 7-8 minutes.

After performing the stretching protocols, post-intervention hip extension ROM measures will be immediately obtained and followed by measurements of dynamic balance or knee JPS. All testing and intervention procedures will be performed in a single session (45-50 minutes).

Instrumentation. A digital Protractor PRO 3600 inclinometer and a 5th generation Apple iPod touch device integrated with custom made application software will be utilized to measure hip extension ROM and knee JPS in both experimental groups, respectively. A microFET2 handheld dynamometer will be used during HR-PNF stretching protocol to assure consistency of the force applied to the thigh. The star excursion balance test (SEBT) using the Y-Balance test kit will be utilized to measure the dynamic balance performance. Length of the subject's legs will be measured using a tape measure.

Hip extension ROM test. To measure hip extension ROM, the modified Thomas test will be used. The participants will be instructed to sit as close as possible to the edge of the table and to pull their knees to their chest, and then to gently lay down on the table. From this position, one of the lower limbs will be released, allowing the hip to extend toward the floor; while keeping the other knee to the chest. The examiner will observe the thigh to ensure that it is completely relaxed and will position the knee joint at about 80-90° of flexion before measuring hip extension ROM. Then, the digital inclinometer will be placed on the mid-point of the anterior aspect of the thigh being tested. The average value of these 3 trials will be used for statistical analysis.

Knee JPS test. The Apple iPod touch will be utilized to measure knee JPS of the dominant knee for all participants. Subjects will sit comfortably on the treatment table, with their legs hanging off toward the ground. They will be barefoot and dressed in shorts during the test. The iPod will be strapped to the lateral side of the subject's dominant shank. At this point, subjects will close their eyes. Then, a voice from the software will instruct the participants to go through various positions of the knee joint angles. Thirty and 60° of knee flexion will be used to measure knee JPS in this study. Continuous beeps will prompt subjects to extend the knee at the start of each trial and stop when target angle is reached. That position will be held for 5 seconds. Next, an audible sound 'relax' will direct subjects to go back to starting position. Three seconds later, another beep will prompt subjects to try to reproduce the target knee position. The accuracy of the reproduction of joint position will be represented as a constant error (CE) [17].

Dynamic balance test. The Y-Balance test kit will be utilized during the SEBT [18] to measure dynamic balance at pre- and post-interventions tests for all participants. The subject will stand on stance leg on the center of the Y-test kit which extends into 3 lines. These lines are named according to the direction of reach relative to the stance leg: anterior, posterolateral, and posteromedial. While maintaining a single-leg stance on the stance foot, participant will try to push the sliding piece of wood on each extending line as far as possible using their contralateral foot. The distances reached, will be recorded and normalized to the length of subjects' leg [19]. The mean value of the 3 trials during the pre- and post-interventions measurements will be used for statistical analysis.

6. **Give specific examples (with literature citations) for the use of your test instruments/ questionnaires, or similar ones, in previous similar studies in your field.**

Hip extension ROM is usually tested using the modified Thomas test [20–22.] In this study digital inclinometer will be used to measure the hip extension ROM during the modified Thomas test. This technique has been used in several previous studies [20,23–25.]

Apple iPod device integrated with custom-made software has been utilized to measure JPS (i.e. accuracy of joint angle reproduction) in a number of previous studies [26,27]. This device provides a direct measurement of JPS. In this study, the iPod touch integrated with custom-made software was used to electronically measure the accuracy of joint angle replication.

Assessment of dynamic balance performance using SEBT has been used in several previous studies [28–31]. The SEBT with its “Y” configuration (i.e. anterior, posteromedial, and posterolateral directions) [19] will be used in this study to assess the dynamic balance performance.

7. **Describe how your study design is appropriate to examine your question or specific hypothesis. Include a description of controls used, if any.**

The proposed study will use a pretest-posttest randomized experimental groups design. There will be two treatment groups, group A will perform dynamic stretching protocol and group B will undergo HR-PNF stretching protocol. The main experimental question will be addressed by examining the acute effects of these two stretching techniques on hip extension ROM, knee JPS and dynamic balance performance. This study design is appropriate as each subject will serve as their own control (i.e. pre-to post-intervention measurements within the group) and will permit for comparison between the experimental groups (i.e. between groups). Thus, changes seen in hip extension ROM, knee JPS and dynamic balance performance can then be attributed to the type of stretching protocol used and not due a learning effect of the assessment procedures, passage of time, or any other factors.

8. **Give specific examples (with literature citations) for the use of your study design, or similar ones, in previous similar studies in your field.**

Our study design has been used by several previous studies. Similar studies have been conducted utilizing two treatment groups to evaluate the acute effects of two stretching techniques on multiple variables [7,29,32].

9. **Describe the potential risks to the human subjects involved.**

Potential risks include falling during the SEBT. Dynamic and HR-PNF stretching techniques may cause some muscle soreness.

10. If the research involves potential risks, describe the safeguards that will be used to minimize such risks.

To minimize the muscle soreness resulting from stretching protocols, all participants will perform a 5-minute warm-up by jogging on a treadmill at a comfortable self-selected speed before performing the designated stretching protocol. A research assistant will be standing near the subject during the Star Excursion Balance Test to help them maintain balance in case they start to fall.

11. Describe how you will address privacy and/or confidentiality.

The data of the subjects will be coded with no reference to their name, sex or other identifying demographic information. Informed consent and data collection sheets will be kept in a locked filing cabinet at the Biomechanics lab. The data will not be associated with subject's identity in any presentation or publication.

12. If your research involves the use of schools (pre-kindergarten to university level) or other organizations (e.g., community clubs, companies), please attach a clearance letter from an administrator from your research site indicating that you have been given permission to conduct this research. For pre-kindergarten to grade 12 level schools, an administrator (e.g. principal or higher) should issue the permission. For post-secondary level schools, the class instructor may grant permission. For Western Washington University, this requirement of a clearance letter is waived if you are recruiting subjects from a scheduled class. If you are recruiting subjects from a campus group (not a class) at Western Washington University, you are required to obtain a clearance letter from a leader or coordinator of the group.

My research does not involve the use of schools or other organization.

13. If your research involves the use of schools (pre-kindergarten to university level) or other organizations (e.g., community clubs, companies), and you plan to take still or video pictures as part of your research, please complete a) To d) below:

My research does not involve the use of schools or other organization. However, we do plan to use photographic or video recording for the following purposes:

- publishing the results of the research
- conference presentations
- educational presentations or courses
- informational presentations
- on-line educational courses
- educational videos

Please see attached Photograph and Video release form.

Appendix: B

Western Washington University

Consent to Take Part in a Research Study

Project: Acute effects of two hip flexor stretching techniques on knee joint position sense and Balance

You are invited to participate in a research study conducted by Hussain I. Younis Aslan, graduate student, from the department of Health and Human Development at the Western Washington University. The purpose of this study is to investigate the acute effects of two hip flexor stretching techniques on knee joint position sense and balance. You are selected as a possible participant in this study because you are 18-28 years old (male, female), physically active (i.e. participate in any type of physical activity such as walking, or sport for a minimum of 30 minutes, 3-4 days/week), and have no history of pain, injury, pathology and/or surgery in low back, hips, lower extremity, as well as not having neurological or vestibular impairments (i.e. chronic dizziness or imbalance that results from disorders in the inner ear and parts of the brain), however, with a possibility of having tight hip flexors. The results of this investigation will improve our understanding of the effectiveness of these two stretching techniques in reversing tight hip flexors, and affecting knee joint position sense and dynamic balance performance. The results will also give us a better understanding of how these stretching techniques may be used in improving performance and in rehabilitation programs.

All measurements used in this study are non-invasive. If you meet the inclusion criteria of having tight hip flexors and decide to participate, you understand that the following things will be done to you:

1. This experiment will begin by filling out a brief form to provide basic information such as name, gender, age, and a short health history and physical activity questionnaire as well as photograph and video release form. We will be videotaping and/or taking pictures of you during the tests and stretching protocols of this research for the purpose of publishing and presentations.

2. Then, measurement of height, weight, length of leg, and determination of dominant leg will be conducted. The major tests of this study will start with measuring hip extension range of motion of both hips followed by performing Star Excursion Balance Test. Next, knee joint movements will be evaluated with an iPod device attached by your ankle. Following these tests, you will warm up by jogging on a treadmill for 5 minutes on self-selected comfortable pace. Then, you will perform a short stretching with my help. Immediately after stretching, the three tests will be performed again. The participation in this experiment requires a single session with approximate duration of 45-50 minutes.

3. There may be some risks during the dynamic balance test such as falling but a spotter will be close by to minimize this risk. The stretching techniques may cause some muscle soreness but this soreness will subside gradually within few days after the experiment. The primary investigator has several years of experience practicing these stretching techniques, you can communicate with him during or after the procedure in case of

feeling discomfort. Possible benefits may be reflected as improved motion on your hip, improved posture, balance, and knee joint position sense.

4. Participation in this study is voluntary and there is no compensation for your participation. You have the right to withdraw your consent and discontinue participation at any time during the experiment without penalty.

5. All information collected throughout the experiment is anonymous and confidential. Your signed consent form will be saved in a secured cabinet separate from the data collection forms. Your name will not be associated with any of your data collected during this research study. Instead, a 3-digit random number will be used in your data collection sheet.

6. Your signature on this form does not waive your legal rights of protection.

7. This experiment is conducted under the supervision of Dr. Jun San Juan (Health and Human Development). Any questions that you have about the experiment or your participation may be directed to Dr. Jun San Juan at (360) 650- 2336.

If you have any questions about your participation or your rights as a research participant, you can contact Janai Symons, Research Compliance Officer, Janai.symons@wwu.edu and (360) 650-3082.

If during or after participation in this study you suffer from any adverse effects as a result of participation, please go to the Student Health Center to get checked and notify Dr. Jun San Juan (360-650-2336; jun.sanjuan@wwu.edu), or contact Janai Symons, Research Compliance Officer, Janai.symons@wwu.edu and (360) 650-3082.

I have read the above and previous page description, agree to participate in this research study, and am 18 years or older.

______________________________________ ______________________

Participant’s Signature Date

______________________________________ ____________

Participant’s PRINTED NAME Subject #

Note: Please sign both copies of the form and keep the copy marked “Participant” for your own records.

Appendix: C

Data Collection Sheet and Procedures Check-off List

Subject #________. Gender: ________. Age: ________ yr.
Height: ________cm. Weight: ________kg.
Leg Length: ________cm. Mid-thigh verified________ Right_______ Left.
Dominant Leg_________Right________Left.
Group A- Dynamic stretches: ______________. Group B- HR-PNF stretches______________.
Data Collection Time: ______________ Date____/____/_________.
Consent Form Completed_______Yes. ______No.
All tests performed barefoot_______Yes. ______No.
Warm up between pre- and post-intervention_____ Yes. ______No.

Hip Extension ROM Test
Instructed of procedure_______Yes. ________No. Include ________Yes. ________No.

	Pre			Post (immediate)			Post 5 minutes		
	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
Left Hip (°)									
Right Hip (°)									

Knee JPS
Attached iPod device _______Yes. ________No.
Instructed of procedure_______Yes. ________No.
Eyes closed_________________Yes. ________No.
Arms crossed around chest_______Yes. ________No.

	Pre			Post		
	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
Knee flexion at 30°						
Knee flexion at 60°						

Star Excursion Balance test
Leg length measured _______Yes. ________No.
Instructed of procedure_______Yes. ________No.
One practice trial____________ Yes. ________No.
Randomized order____________Yes. ________No.

	Pre			Post		
	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
Anterior (cm)						
Posteromedial (cm)						
Posterolateral (cm)						

Appendix D:

Screening of Health History and Physical Activity Questionnaire

Name: ____ Subject #___________________.
Gender: _________.
Age: _______ yr.
Date: ____/____/________.

Time: ________________.

A. Screening Inclusion Criteria (*YES* option must be checked for all participants)

1. Are you between the ages of 19 and 25 years old?

_____Yes _______No.

2. Are you a recreationally active person (participate in a type of physical activity or sport for a minimum of 30 minutes, 3-4 days/week for the past 3 months)?

_____Yes _______No.

B. Screening Exclusion Criteria (*NO* option must be checked for all participants)

1. Have you had any pain and or injury in the hips, groin area, lower back, and lower extremity that prevent you from stretching your hip and thigh muscles within the last 6 months? Yes__________ No__________.
2. Have you participated in any of balance or proprioceptive or training within the past 6 months? Yes__________ No__________.

3. Have you had any surgery in the lower back, hips and lower extremity within the past 6 months? Yes__________ No__________.
4. Have you had any vestibular disorder within the past 6 months? Yes_______No______.
5. Do you have any medical condition that may impair your balance performance (i.e. concussion, neurological impairments, orthopedic problems etc.)? Yes_____No______.

C. Exercise/Sporting Activity

1. Type of exercise or sport activity: ____.
2. Total of weekly participation time (minutes): ___________.

Appendix: E

Photograph & Video Release Form

I hereby grant permission to the rights of my image, likeness and sound of my voice as recorded on audio or video tape without payment or any other consideration. I understand that my image may be edited, copied, exhibited, published or distributed and waive the right to inspect or approve the finished product wherein my likeness appears. Additionally, I waive any right to royalties or other compensation arising or related to the use of my image or recording. I also understand that this material may be used in diverse educational settings within an unrestricted geographic area.

Photographic, audio or video recordings may be used for the following purposes:

- conference presentations
- educational presentations or courses
- informational presentations
- on-line educational courses
- educational videos

By signing this release, I understand this permission signifies that photographic or video recordings of me may be electronically displayed via the Internet or in the public educational setting. I will be consulted about the use of the photographs or video recording for any purpose other than those listed above.

There is no time limit on the validity of this release nor is there any geographic limitation on where these materials may be distributed.

This release applies to photographic, audio or video recordings collected as part of the sessions listed on this document only.

By signing this form, I acknowledge that I have completely read and fully understand the above release and agree to be bound thereby. I hereby release any and all claims against any person or organization utilizing this material for educational purposes.

Full Name____

Street Address/P.O. Box____

City ____

Postal Code/Zip Code_______________________________________

Phone _____________________________ Fax ________________________

Email Address____

Signature______________________________ Date______________________________

If this release is obtained from a presenter under the age of 19, then the signature of that presenter's parent or legal guardian is also required.

Parent's Signature______________________ Date______________________________

Appendix: F

Raw Data

Mean of Hip Extension ROM

Dynamic Stretching Group:

Subject #	Pre-stretch		Post-immediate of stretch		Post-5min. of stretch	
	R. hip°	L. hip°	R. hip°	L. hip°	R. hip°	L. hip°
M 6	6.03	11.30	2.65	0.81	8.15	-2.51
M 8	5.42	5.80	2.77	3.85	5.07	-0.91
M 9	9.28	9.33	6.76	4.19	3.24	3.92
M 12	10.09	9.84	3.61	6.34	8.84	11.33
M 13	8.03	10.92	6.10	9.52	11.50	10.27
M 17	7.84	10.57	3.18	4.29	1.90	2.84
M 20	6.57	6.11	0.93	-3.89	0.58	0.65
M 22	6.38	10.38	4.08	2.04	4.26	1.17
M 24	7.62	5.00	1.03	-3.66	0.49	-2.36
M 27	12.70	11.67	7.04	7.78	3.79	4.81
M 29	9.78	7.25	6.18	4.16	3.65	0.62
M 31	13.13	10.47	11.60	5.82	6.93	5.50
F 5	9.27	8.16	-4.14	-6.07	0.69	-1.37
F 8	6.08	5.63	2.55	-0.56	1.00	7.33
F 9	14.37	11.73	11.02	10.35	11.37	7.74
F 12	13.90	7.30	3.40	2.89	2.40	-0.13
F 14	9.89	9.75	7.10	6.05	3.77	8.10

M=male, F=female.

Mean of Hip Extension ROM

PNF Stretching Group:

Subject #	Pre-stretch		Post-immediate of stretch		Post-5min. of stretch	
	R. hip°	L. hip°	R. hip°	L. hip°	R. hip°	L. hip°
M 7	10.29	11.48	-1.38	2.03	1.01	2.81
M 10	6.94	5.87	-5.78	-9.92	-5.61	0.31
M 11	8.07	7.01	0.14	-3.22	4.21	2.67
M 14	9.32	14.60	-3.67	-2.13	-7.86	-2.01
M 15	11.75	12.93	-2.18	-4.84	-0.44	0.96
M 16	7.11	7.26	-6.19	-6.46	-1.41	1.11
M 19	7.15	6.38	-8.46	-4.03	-1.02	-3.69
M 23	10.70	12.33	2.06	4.91	6.82	5.61
M 25	8.61	11.43	-3.87	2.90	0.97	2.37
M 26	9.77	14.03	6.11	3.69	6.11	3.69
M 28	12.20	14.07	3.34	0.33	2.19	1.86
M 30	7.55	12.80	-2.26	-0.27	-0.61	0.99
F 2	13.20	8.56	-19.73	-15.23	-19.03	-15.50
F 6	5.22	6.56	-10.52	-8.01	-2.89	-2.46
F 10	13.93	6.99	-5.96	-3.33	5.01	0.63
F 11	12.53	13.73	1.67	-0.81	1.91	-2.44
F 13	6.23	6.82	-10.14	-2.87	-4.94	-2.23
F 15	11.09	13.33	-2.86	2.66	-0.56	0.63

M=male, F=female.

Mean of JPS Replication Error

Dynamic Stretching Group:

Subject #	Pre-stretch		Post-stretch	
	Angle 30°	Angle 60°	Angle 30°	Angle 60°
M 6	3.36	-2.76	2.53	0.50
M 8	9.16	3.10	10.13	2.90
M 9	2.60	1.06	5.90	2.07
M 12	6.13	2.00	7.83	4.17
M 13	4.20	3.63	2.33	1.90
M 17	5.30	-1.43	7.40	4.03
M 20	10.23	1.56	9.10	3.80
M 22	8.60	7.30	6.57	4.07
M 24	3.86	-1.76	0.30	-2.50
M 27	3.87	-1.77	0.30	-2.50
M 29	6.73	3.20	0.07	-3.10
M 31	7.27	-4.83	6.93	2.03
F 5	7.60	1.30	7.27	0.47
F 8	3.77	3.03	2.97	3.60
F 9	7.37	3.75	12.53	2.67
F 12	3.03	-0.57	5.67	2.77
F 14	8.80	0.70	6.90	3.33

M=male, F=female.

Mean of Knee JPS Replication Error

PNF Stretching Group:

Subject #	Pre-stretch		Post-stretch	
	Angle 30°	Angle 60°	Angle 30°	Angle 60°
M 7	8.73	0.33	9.63	2.50
M 10	8.80	2.77	5.63	-0.17
M 11	0.47	-1.37	3.07	0.40
M 14	4.10	0.30	3.83	4.10
M 15	-0.37	2.63	4.23	2.00
M 16	14.67	-0.30	6.97	-1.07
M 19	5.76	2.80	4.86	1.27
M 23	3.43	0.70	1.50	1.80
M 25	6.60	2.10	1.10	0.20
M 26	11.30	11.63	9.37	5.50
M 28	1.57	4.43	3.33	3.73
M 30	5.70	2.30	4.73	1.60
F 2	4.00	-3.27	7.93	0.57
F 6	10.17	2.23	5.73	15.26
F 10	-2.17	-0.37	-1.87	2.80
F 11	7.83	3.53	4.53	1.10
F 13	15.93	6.70	14.33	7.73
F 15	5.70	1.07	5.73	-1.20

M=male, F=female.

Mean of Dynamic Balance Measures (Normalized Values, %)

Dynamic Stretching Group:

Subject #	Pre-stretch			Post-stretch		
	Anterior %	Postero-medial %	Postero-lateral %	Anterior %	Postero-medial %	Postero-lateral %
M 6	63.86	98.22	100.94	63.39	106.27	107.96
M 8	70.97	103.02	106.23	64.74	109.62	111.72
M 9	53.62	94.34	102.44	53.22	101.73	104.09
M 12	64.68	112.03	115.06	64.11	105.78	115.25
M 13	58.25	84.76	99.75	63.72	96.97	103.20
M 17	61.00	96.92	102.25	65.50	104.92	107.75
M 20	61.98	105.12	107.38	72.31	102.86	100.69
M 22	56.32	93.51	101.23	60.51	100.16	104.76
M 24	59.24	104.84	110.19	61.83	110.02	121.24
M 27	63.33	103.62	113.62	64.38	110.67	114.48
M 29	74.56	122.28	126.67	75.26	129.47	129.82
M 31	64.95	107.71	123.24	64.38	115.90	124.19
F 5	81.03	109.44	125.54	78.87	111.49	128.10
F 8	66.46	116.46	109.70	65.96	118.79	115.25
F 9	64.52	101.70	111.02	63.17	102.15	113.17
F 12	64.22	93.30	98.37	61.78	101.90	108.33
F 14	68.65	94.69	97.71	72.71	104.48	108.85

M=male, F=female.

Mean of Dynamic Balance Measures (Normalized Values, %)

PNF Stretching Group:

Subject #	Pre-stretching			Post-stretching		
	Anterior %	Postero-medial %	Anterior %	Postero-medial %	Anterior %	Postero-medial %
M 7	68.33	101.94	109.54	65.28	106.67	112.22
M 10	80.21	117.97	122.57	83.68	124.05	126.04
M 11	67.68	98.15	106.06	68.77	96.30	104.29
M 14	69.10	110.58	125.28	74.44	119.01	125.66
M 15	68.68	98.33	110.88	70.35	103.42	117.63
M 16	56.34	87.77	93.48	62.86	86.23	90.40
M 19	70.18	125.15	129.43	69.49	123.10	124.56
M 23	69.55	110.34	122.73	66.84	113.10	122.01
M 25	72.00	125.56	124.16	69.57	120.69	126.22
M 26	63.08	100.18	103.67	63.17	110.39	101.34
M 28	73.02	106.08	120.26	76.24	120.07	121.55
M 30	63.77	110.79	117.72	72.54	111.75	122.72
F 2	72.02	116.98	123.25	72.94	119.86	123.97
F 6	60.66	92.03	101.43	57.17	82.53	99.37
F 10	71.90	88.47	99.98	69.09	95.93	105.14
F 11	66.31	100.44	102.82	64.64	103.53	104.14
F 13	70.40	97.45	111.48	72.77	102.73	115.03
F 15	66.13	103.69	107.57	66.40	105.23	110.72

M=male, F=female.