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The purpose of this study was to investigate the relationship between hamstring extensibility and pelvic tilt, and their collective impact on hamstring strength. The first objective was to examine the relationship between anterior pelvic tilt and hamstring extensibility, with the hypothesis that increased anterior pelvic tilt would be associated with increased hamstring extensibility. The second objective was to examine the relationship between anterior pelvic tilt, hamstring extensibility and the strength of the hamstring muscle group. It was hypothesized that greater angles of anterior pelvic inclination and greater hamstring extensibility would be associated with lower torque production of the hamstring muscle group after accounting for anterior muscle tightness and genu recurvatum. The participants of this study included 43 NCAA Division IAA student-athletes from the University of North Carolina at Greensboro. Subjects were tested for pelvic inclination and hamstring extensibility as part of a station-to-station preseason screening, while hamstring strength was collected isokinetically in a separate test session. No significant relationships were noted between pelvic angle, hamstring strength and hamstring extensibility, despite accounting for the additional variables of genu recurvatum and anterior muscle tightness. However, a significant negative correlation was found between anterior muscle tightness and hamstring extensibility, but only on the left side. Further study is needed to understand the relationship between posture, muscle extensibility and muscle strength.

THE RELATIONSHIP BETWEEN ANTERIOR PELVIC TILT, HAMSTRING EXTENSIBILITY AND HAMSTRING STRENGTH

by

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APPROVAL PAGE

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CHAPTER I

INTRODUCTION

Henry and Florence Kendall (2005) proposed that four muscle groups are responsible for supporting the pelvis in its anteroposterior alignment: the erector spinae, hamstrings, abdominals and hip flexors, and suggest that when all the muscles are in balance the pelvis is maintained in a neutral alignment. However, if muscle imbalance occurs, the pelvis is thought to tilt anteriorly or posteriorly, with the pelvis more frequently tilting anteriorly (Kendall, McCreary, Provance, Rodgers, & Romani, 2005; Nguyen & Shultz, 2007). This is thought to result from one or a combination of tight hip flexors or erector spinae muscle, and/or weakened and lengthened abdominal or hamstring muscles (Kendall, McCreary, Provance, Rodgers, & Romani, 2005). While the ideal posture has not been universally agreed on, excessive anterior inclination of the pelvis has generally been regarded in the past as undesirable (Day, Smidt & Lehmann, 1984; During, Goudfrooij, Kessen, Beeker, & Crowe, 1985; Toppenberg & Bullock, 1986; Toppenberg & Bullock, 1990; Gajdosik, 1991; Christie, Kumar, & Warren, 1995; Hruska, 1998; Nourbakhsh & Arab, 2002; Kendall et al., 2005). Specifically, anterior pelvic tilt is thought to be associated with low back pain (Day et al., 1984; Toppenberg & Bullock, 1986; Roncarati & McMullen, 1988; Gadosik, 1991; Gajdoski, Hatcher & Whitesell, 1992; Hruska, 1998; Kendall et al, 2005), strength deficits of the hamstring and gluteal muscles (Kendall et al., 2005), greater genu recurvatum (Kendall et al., 1983; Hruska, 1998), and an increased risk of ACL injury (Loudon, Jenkins & Loudon, 1996; Hertel, Dorfman & Braham, 2004).

One potential mechanism by which clinicians have associated anterior pelvic tilt with these conditions is that anterior pelvic tilt is thought to result in a lengthened and weakened hamstring muscle group (Hruska, 1998; Kendall et al., 2005). This in turn is thought to contribute to a decrease in biomechanical efficiency and functional capacity at the hip and knee (Grossman, Sahrmann & Rose, 1982; Grossman, Delittto, & Rose, 1983; Grossman, Clendaniel, Delitto, Katholi & Rose, 1984; Janda, 1993). Given that the origin of the hamstring attaches on the ischial tuberosity of the pelvis, it is logical that the orientation of the pelvis may influence the tension in the hamstring muscles group (and visa versa) (Martin, 1968; Toppenberg & Bullock, 1986; Link, Nicholson, Schaddeau, Birch, & Grossman, 1990; Gajdosik et al., 1992; Gajdosik, Albert & Mitman., 1994; Li, McClure, & Pratt, 1996; Congdon, Bohannon, & Tiberio, 2005; Kendall et al., 2005). As skeletal muscle is known to perform best at an optimal length, an alteration in the length-tension relationship of the hamstring muscles could potentially alter their ability to generate maximal force. Studies investigating the relationship between imposed muscle length and torque production of the hamstring muscles found a linear relationship between hip angle and peak torque (Grossman et al., 1983; Grossman et al., 1984). This research looked at torque differences between subjects with long and short hamstrings. Tighter hamstrings were associated with larger magnitudes of force, regardless of imposed length. These results suggest the longer muscles may have less force producing capabilities due to their elongated position, which is consistent with the ideas of Kendall et al. (2005).

Decreased hamstring muscle strength has been suggested to be a risk factor associated with various lower extremity injuries (Knapik, Bauman, Jones, Harris, & Vaughan, 1991), including hamstring muscle strains (Orchard, 2001; Croisier, Forthomore, Namurois, Vanderthommen, & Crielaard, 2002; Askling, Karlsson, & Thorstensson, 2003; Verrall, Slavotinek, Barnes, & Fon, 2003; Croisier, 2004; Petersen & Hölmich, 2005; Brooks, Fuller, Simon, Kemp & Reddin, 2006;) and ACL injuries (Lloyd, 2001; Söderman, Alfredson, Pietilä, & Werner, 2001; Anderson, Dome, Gautam, Awh & Rennirt, 2001). Should an increase in anterior pelvic tilt be associated with weakened and lengthened hamstring muscles as clinically described, this may predispose an individual to a greater potential for hamstring or ACL injury as a result of decreased hamstring force production capabilities. But while biomechanical concepts suggest a possible relationship between hamstring length and pelvic inclination (Yoon, Dong, Kang, Chun, & Shin, 1991; Brockett, Morgan, & Proske, 2001; Mohamed, Perry, & Hislop, 2002; Onishi, Yagi, Oyama, Akasaka, Ihashi, & Handa, 2002), empirical studies examining this relationship and their effect on hamstring muscle strength is lacking.

Gaining a better understanding of whether pelvic orientation (i.e. pelvic tilt) is indeed associated with greater hamstring extensibility and reduced hamstring strength will advance our understanding of factors contributing to postures in both asymptomatic and symptomatic populations that may lead to an increased risk for injury.

Statement of the Problem

The relationship between pelvic inclination, hamstring extensibility and hamstring strength has not been adequately explored. While Kendall et al (2005) and others (Link et al., 1990; Hruska, 1998; Starkey & Ryan, 2002) suggest a possible connection between weak hip extensors and anterior pelvic tilt, empirical, well controlled studies are lacking. If anterior pelvic tilt does in fact lead to potentially lengthened and weakened hamstrings, athletes with an anterior pelvic tilt may have compromised hamstring strength leading to a greater predisposition to injury. Therefore the purpose of this study was to investigate the relationships between hamstring extensibility and pelvic tilt, and their collective impact on hamstring strength.

Objectives

1. The first objective was to examine the relationship between anterior pelvic tilt and hamstring extensibility.

   Hypothesis 1: Increased anterior pelvic tilt will be associated with increased hamstring extensibility.

2. The second objective was to examine the relationship between anterior pelvic tilt, hamstring extensibility and the strength of the hamstring muscle group.

   Hypothesis 2: Greater angles of anterior pelvic tilt and greater hamstring extensibility will be associated with lower torque production of the hamstring muscle group after accounting for anterior muscle tightness and genu recurvatum.

Assumptions

1. Pelvic inclination can be reliably measured with sufficient accuracy and precision.
2. The active knee extension (AKE) test is a valid and reliable method of testing hamstring extensibility.
3. It is assumed that minimal strength gains will occur in the three weeks between pre-season screening and the collection of muscle strength data.
4. Strength testing will be performed isokinetically using an concentric/eccentric protocol which is assumed to adequately represent the functional strength of the hamstring muscle group.

Delimitations

1. Only female subjects will be evaluated to avoid other sex confounding factors that may influence the relationships between pelvic inclination, muscle extensibility and thigh strength.
2. Pelvic inclination and hamstring extensibility will be measured using clinical measurement techniques.
3. Only female college-aged volleyball players, cross-country runners and soccer players will be studied. The age range will be limited to 18 to 24.
4. The testing position for hamstring strength will take place in the seated position, while pelvic inclination will be tested in the standing position.

Limitations

1. It will not be possible to generalize findings of this study to males.
2. It will not be possible to generalize the findings of this study beyond the college age population.
3. It may not be possible to generalize the findings of this study beyond the population of athletes studied (volleyball, cross-country, and soccer).
4. Functional strength capabilities will not be directly measured.
5. Pelvic angle may not be consistent during seated isokinetic testing and the standing measurement of pelvic tilt.

Operational Definitions

<u>Neutral Pelvis</u>. The position of the pelvis when the line between the anterior superior iliac spine (ASIS) and the posterior superior iliac spine (PSIS) is parallel to the horizontal plane.

<u>Pelvic Tilt.</u> The degree to which the position of the pelvis (a line between the ASIS and PSIS) deviates from the horizontal plane when viewed in the sagittal plane, as determined with a pelvic inclinometer.

<u>Anterior Pelvic Tilt.</u> An angle of inclination in which the anterior superior iliac spine (ASIS) is inferior to the posterior superior iliac spine (PSIS) in relation to the horizontal plane.

<u>Hamstring Extensibility.</u> The amount of active knee extension while the hip is maintained at 90 degrees of flexion using an active knee extension (AKE) test.

Concentric Hamstring Peak Torque. The maximum torque applied during a single shortening contraction of the knee flexors against a lever arm that is rotating at an angular velocity of 180°/second from 0 – 90° of knee flexion.

Eccentric Hamstring Peak Torque. The maximum torque applied during a single lengthening contraction of the knee flexors against a lever arm that is rotating at an angular velocity of 90°/second from 0 – 90° of knee flexion.

Athlete. Any active and medically cleared participant of the women's volleyball, cross country or soccer team at the University of North Carolina at Greensboro, a NCAA Division IAA institution.

Genu Recurvatum. The amount of maximum active knee hyperextension while positioned supine and measured in degrees as the angle formed between the greater trochanter, lateral joint line and lateral malleolus using a standard goniometer.

Hip Flexor Tightness. Hip flexor tightness will be determined as the amount of hip range of motion while lying supine and the opposite knee drawn into the chest using the Thomas Test.

Anterior Muscle Tightness. Determined by the results of the Thomas Test; a test revealing either hip flexor or rectus femoris tightness will be classified as anterior tightness.

CHAPTER II

LITERATURE REVIEW

This review will focus on research that has investigated anterior pelvic tilt and hamstring extensibility, and its potential relationship to the strength of the hamstring muscle group. The clinical relevance of decreased hamstring strength will be presented, followed by a deeper analysis of anterior pelvic tilt and the muscle groups associated with the orientation of the pelvis. As anterior pelvic tilt is generally regarded as an undesirable posture, the potential clinical consequences of this posture will also be discussed. Finally, due to the variety of measurement procedures used to examine pelvic tilt and hamstring extensibility and strength, the various measurement issues will be discussed to provide a rationale for the measurement methods chosen for this study.

Role of the Hamstring Muscles in Injury Prevention

It has been proposed that decreased hamstring muscle strength is a risk factor associated with various injuries to the lower extremity, including hamstring muscle strains (Orchard, 2001; Croisier et al., 2002; Askling et al., 2003; Verrall et al., 2003; Croisier, 2004; Petersen & Hölmich, 2005; Brooks et al., 2006) and ACL injuries (Anderson et al., 2001; Lloyd, 2001; Söderman, Alfredson, Pietilä, & Werner, 2001). Hamstring strains are among the most common soft tissue injuries seen in sports involving sprinting and jumping (Ekstrand & Gillquist, 1983; Orchard & Seward, 2002; Arnason, Sigurdsson, Gudmundsson, Holme, Engebrestsen, & Bahr, 2004; Woods, Hawkins, Maltby, Hulse, Thomas & Hodson, 2004). Factors such as lack of flexibility, fatigue, inadequate warm-up, previous injury, age, muscle imbalance and muscle weakness have been speculated as predisposing factors of hamstring strains (Verrall, 2001; Orchard & Seward, 2002; Croiser et al., 2002; Woods, et al., 2004; Brooks et al., 2006). Of the limited evidence based studies examining the risk factors associated with hamstring muscle injuries, several prospective studies have shown decreased hamstring strength to be associated with increased incidence of hamstring injury (Söderman et al., 2001; Croisier et al., 2002; Askling et al., 2003; Brooks et al., 2006). Further, previous hamstring injuries are one of the primary risk factors for sustaining a subsequent hamstring injury (Arnason et al., 2004; Woods et al., 2004; Gabbe, Bennell, Finch, Wajswelner, & Orchard, 2006). Reinjury may result from not adequately regaining hamstring strength and proper balance between the quadriceps and hamstring muscles following the initial injury, leaving the weakened hamstring muscle susceptible to a reduced threshold to similar demands (Croiser et al., 2002).

A decreased hamstring to quadriceps muscle ratio (H:Q ratio), has previously been identified as a risk factor for knee injuries (Knapik et al., 1991), particularly, ACL injuries (Anderson et al., 2001; Lloyd, 2001; Söderman et al., 2001; Bowerman, Smith, Carlson, & King, 2006). One study reported that athletes with hamstring strength less than 75% of the quadriceps muscles at 180°/sec were 1.6 times more likely to suffer from ACL injury than athletes with stronger hamstrings in relation to the quadriceps (Knapik et al., 1991). Another study investigated sex differences in relation to the occurrence of ACL injury and identified a significant difference in the hamstring to quadriceps ratio between male and female athletes (Anderson et al., 2001). The ratio was significantly greater for males, indicating females had relatively weaker hamstrings (Anderson et al., 2001). Hamstring strength is considered an essential component to reduce the risk of ACL injury because the hamstring muscle group is positioned to counteract the force created by the quadriceps muscles, thereby reducing the amount of anterior tibial translation and strain on the ACL (More, Karras, Neiman, Fritschy, Woo & Daniel, 1993; Draganich & Vahey, 1990; Baratta, Solomonow, Zhou, Letson, Chuinard & D'Ambrosia, 1988; Renström, Arms, Stanwyck, Johnson & Pope, 1986).

Given the functional importance of hamstring muscle strength in injury prevention, it is important to understand the factors that may compromise the muscles strength capabilities. One such factor is a posture characterized by greater anterior pelvic tilt.

Pelvic Inclination

Since 1949 Henry and Florence Kendall (2005) have proposed that four muscle groups are responsible for supporting the pelvis in its anteroposterior alignment: the errector spinae, hamstrings, abdominals and hip flexor muscles. This assumed relationship is based on the origin and insertion of these muscles and their potential to act on the pelvis. When all four muscles are in balance, the pelvis is thought to be maintained in a more neutral alignment (Kendall et al., 2005). However, if muscle imbalances occur, the pelvis will tend to slope anteriorly or posteriorly. Pelvic tilt is defined as the angle formed between the line connecting the anterior and posterior superior iliac spines (ASIS and PSIS) and the horizontal plane (Pitkin & Pheasant, 1936; Toppenberg & Bullock, 1986, Walker, Rothstein, Finucane, & Lamb, 1987; Toppenberg & Bullock, 1990; Gilliam, Brunt, MacMillian, Kinard & Montgomery, 1994; Li et al., 1996; Nourbakhsh & Arab, 2002; Starkey & Ryan, 2002; Sprigle, Flinn, Wootten, & McCorry, 2003). The pelvis is more frequently tilted anteriorly than posteriorly, and normal standing pelvic tilt is generally considered to be between eight and eleven degrees of inclination between a line from the ASIS to PSIS in reference to the horizontal (Day et al., 1984; Roncartati et al., 1988; Heino, Godges, & Carter, 1990; Gilliam et al., 1994; Levine & Whittle, 1996; Starkey & Ryan, 2002; Hertel, Dorfman, & Braham, 2004; Nguyen & Shultz, 2007). Females commonly present with a posture associated with greater anterior pelvic tilt when compared to males (Kendall et al., 2000; Nguyen & Shultz, 2007), which has been independently associated with an increased risk for ACL injury (Hertel et al., 2004; Loudon et al., 1996).

Muscles Influencing Pelvic Inclination

According to Kendall et al. (2005), anterior pelvic tilt can be the result of a combination of weak anterior abdominal muscles, tight hip flexors (especially iliopsoas), tight low back musculature, and weak hip extensor muscles. Tight low back and weak hip extensors are seldom found as the primary cause, but when found in conjunction with hip flexor shortness and abdominal weakness the associated pelvic tilt and lordosis tend to be more exaggerated (Kendall et al., 2005). In contrast, posterior pelvic tilt or "flat-back" posture is thought to result from a combination of strong or tight low back muscles, strong abdominals (especially lower abs), tight hip extensors and weak hip flexors (Link et al., 1990; Starkey & Ryan, 2002; Kendall et al., 2005). However, it is important to note that these are clinical observations with very little empirical studies available to support these contentions. The following sections will describe what is known about the relationships of each muscle group with pelvic tilt orientation.

Abdominal Muscle Group

Due to the abdominal muscles' attachment on the pelvis, it is logical that when the muscles are activated and in a shortened position relative to an upright posture, the pelvis will tilt posterior, whereas tightness of the lumbar erector spinae muscles will tilt the pelvis anteriorly (Youdas, Garret, Harmsen, Suman, & Carey, 1996; Youdas, Garrett, Egan, Therneau, 2000; Christie et al., 2002; Nourbakhsh & Arab, 2002; Kendall et al., 2005). If the abdominals are lengthened and the lumbar erector spinae muscles are shortened, it is theorized that the degree of anterior pelvic inclination and lumbar lordosis would be greater than normal (Youdas et al., 1996). But, although it has been proven that the abdominals function to tilt the pelvis posteriorly upon contraction in the standing posture (Day et al., 1984), no evidence exists regarding the relationship between the ability of the abdominal muscles to actively contract and maintain the contraction during normal *relaxed* standing posture (Walker et al., 1987). Walker, Rothstein, Finucane, & Lamb (1987) conducted a study to determine the relationship between lumbar lordosis, pelvic tilt and abdominal muscle performance during normal standing posture. Pelvic inclination was measured using an inclinometer and abdominal muscle performance was evaluated using the leg-lowering test, which is a widely accepted and considered to be clinically relevant test to assess abdominal and core strength (Kendall et al., 2005). The patient was positioned supine with the hips flexed and legs vertically position with the knees fully extended. The subject was then asked to slowly lower his or her legs to the beat of a metronome for ten seconds. When the subject's pelvis began to tilt anteriorly, and/or the low back no longer was in full contact with the table the angle between the legs and tabletop was recorded. This procedure was repeated twice, by the same examiner. Within the constraints of the study, this testing procedure was found to be moderately reliable (R^2 = .71). The study revealed no correlation between abdominal muscle function, pelvic tilt (R^2 = .18) or lumbar lordosis (R^2 = .06) as previously postulated. This is supported by other studies that also did not identify an association between weak abdominals and anterior pelvic tilt (Christie et al., 1995; Youdas et al., 2000). However, other work has examined the myoelectric activity of the abdominal muscles during quiet standing and revealed that the muscle group in not active in normal standing posture (Sheffield, 1962). Therefore, it is possible that active abdominal contractions are not responsible for the amount of pelvic inclination during relaxed upright posture. In summary, previous literature suggests the abdominal muscles do not play a critical role in positioning the pelvis in a standing posture. These results suggest other muscles may have more influence on pelvic inclination and lumbar lordosis than previously suspected.

Hip Flexor Muscle Group

The hip flexor muscle group has also received considerable attention regarding their influence on pelvic inclination (Toppenberg & Bullock, 1986; Link et al., 1990; Youdas et al., 1996; Youdas et al., 2000; Nourbakhsh, & Arab, 2002). For decades tight or shortened hip flexors have been associated with an increased anterior pelvic tilt due to the iliopsoas' attachment to the pelvis (Toppenberg & Bullock, 1986; Link et al., 1990; Toppenberg & Bullock, 1990; Schache, Blanch, & Murphy, 2000; Kendall et al., 2005). However, studies have failed to demonstrate a significant relationship between standing pelvic inclination and the length of the hip flexor muscles as determined using the Thomas test (Toppenberg & Bullock, 1986; Youdas et al., 1996; Nourbakhsh & Arab, 2002). Although most of the current literature indicates the hip flexors have little to no impact on pelvic inclination in a standing posture, one study (Link et al., 1990), revealed a significant relationship between hip flexor muscle length and anterior pelvic tilt when comparing pelvic inclination in sitting and standing postures. The study revealed that in the seated posture when the length of the hip flexor muscle group was shortened, the angle of pelvic inclination was decreased when compared to a standing posture in which the hip flexors were lengthened and pelvic inclination was increased (Link et al., 1990).

Pelvic Inclination and Hamstring Extensibility

Due to the orientation of the hamstrings on the ischial tuberosity of the pelvis, it is logical that tension in the hamstring muscles may have an influence on movement of the pelvis (Martin, 1968; Toppenberg & Bullock, 1986; Link et al., 1990; Gajdosik, Hatcher, & Whitsell, 1992; Gajdosik, Albert & Mitman., 1994; Li et al., 1996; Congdon, Bohannon, & Tiberio, 2005; Kendall et al., 2005). However, contrary to the long held notion that shortened or tight hamstrings result in a posterior pelvic posture (Kendall et al., 2005), several research studies have indicated the length of the hamstring muscle group does not significantly influence pelvic inclination in the standing position (Toppenberg & Bullock, 1986; Link et al., 1990; Gajdosik et al., 1992; Gajdosik et al., 1994; Li et al., 1996; Nourbakhsh & Arab, 2002; Congdon et al., 2005). While the primary focus of these studies was on tight hamstring muscles, results from Li et al. (1990) revealed a slight increase in anterior pelvic inclination as a result of increased hamstring extensibility; however the gains were not statistically significant. Toppenberg and Bullock (1986) found the best predictors of lordosis to be the lengths of the abdominals, erector spinae and hamstrings; however, no single muscle length relationship was revealed as being significantly related to the degree of pelvic inclination. In fact, Toppenberg & Bullock (1986) reported that shorter hamstrings were associated with a greater degree of spinal curvature, which conflicts with the belief that hamstrings cause posterior pelvic tilting and flattening of the lumbar lordotic curve (Kendall et al., 2005). Gajdosik and colleagues (1992) examined the influence of short hamstrings on pelvic inclination in standing. The study compared subjects with short hamstrings (SLR < 70°)

and subjects without short hamstrings (SLR > 80°) and discovered little influence on pelvic inclination in standing as a function of hamstring length (Gajdosik et al., 1992). While Link et al. (1990) found a significant relationship between hip flexor muscle length and anterior pelvic tilt; they reported no significance relationships between hamstring extensibility and pelvic inclination.

In summary, the current literature does not lend support to the notion that extensibility of the hamstring muscles is related to pelvic inclination. While most studies did detect a slight positive correlation between the two, it was not to the extent capable of confirming statistical significance. However, these studies were primarily limited to the evaluation of tight hamstring muscles, and no studies could be found that examined the relationship between excessive anterior pelvic tilt and hamstring extensibility. Further, these studies typically examined the relationship between hamstring length and pelvic inclination in isolation, and work by Toppenberg and Bullock (1986) suggest that other factors acting on the hip (e.g. status of other muscle groups, lower extremity posture) may need to be controlled for when examining this relationship.

Clinical Consequences of Anterior Pelvic Tilt

Excessive anterior pelvic tilt is considered to be an undesirable trait and has been related to other pathological conditions including low back pain, strength deficits, postural changes and ACL injuries.

Low Back Pain

Postural deviations can create abnormal stresses on the lumbar spine, including increased shear or compressive forces, which have the potential to lead to excessive wear on the involved articular surfaces (During et al., 1985; Christie et al., 1995; Kendall et al. 2005). Historically, the position of the pelvis and length of muscles attaching to the spine and pelvis have been speculated to be contributing factors to the pathogenesis of low back pain based on the anatomical relationship between the pelvis and lumbar spine (Toppenberg & Bullock, 1986, Toppenberg & Bullock, 1990; Gajdosik, 1991; Christie et al., 1995; Hruska, 1998; Nourbakhsh & Arab, 2002). In an anterior pelvic posture excessive compression is placed posteriorly on the vertebrae and articulating facets. Additional tension is also placed on the anterior longitudinal ligament (Kendall et al., 2005). This undue stress on the structures of the low back may have the potential to predispose an individual with this type of posture to painful conditions of the low back.

Several studies have been conducted to establish if a true relationship exists between an increased anterior pelvic tilt in standing and low back pain. Roncarati and McMullen (1988) found anterior pelvic tilt and lumbar lordosis to correlate with low back pain in a general population. Significant correlations have also been reported between sacral angle (a measure of lordosis) and pathological conditions such as spondylolysis and spondylolisthesis, yet no definite relationship was revealed when investigating pelvic tilt (During et al., 1985; Swärd, Hellström, Jacobsson, & Peterson, 1989). However, one study revealed that changes in sacral angle occurred in accordance with changes in pelvic angle (During et al.,1985), suggesting that increased pelvic inclination may be related to these conditions by virtue of its association with sacral angle. However, the results of most studies failed to establish a significant correlation between subjects with low back pain and an increased angle of anterior pelvic inclination (Christie et al., 1995; Day et al., 1984; Nourbakhsh & Arab, 2002; Youdas et al., 2000). Although a study by Day et al. (1984) did not support the theory that increased anterior pelvic tilt is directly related to low back pain, the article proposed that a more posteriorly positioned pelvis has potential benefits. In this position, the structural stability to the spine is improved due to an increase in intra-abdominal pressure (Day et al., 1984).

Strength Deficits

Skeletal muscle has an optimal length, defined as the length at which the maximum muscle force can be generated (Chang, Su, Wu, & An, 1999; Mohamed et al., 2002). It has been a long held belief that if the pelvis is tilted anteriorly, it may alter the optimal length of a muscle's moment arm, disrupting the ideal functional position of the joint. Hence, an alteration in the orientation of the muscle could potentially affect its ability to generate maximal force. Muscles in an altered length are thought to undergo physiological changes (Grossman et al., 1982; Janda, 1993). According to Kendall et al. (2005), "stretch weakness" is defined as a weakness resulting from a muscle remaining in an elongated state. The extent of elongation is not as critical as the duration of time the muscle is exposed to the elongated position. This phenomenon requires the muscle to be only slightly lengthened beyond the neutral physiological resting position (Janda, 1993; Kendall et al., 2005; Grossman et al., 1982). Occupational and postural strain are frequent culprits of stretch weakness. The muscles most typically affected include: gluteus medius and minimus, iliopsoas, hip external rotators, abdominal muscles, and middle and low trapezius (Kendall et al., 2005). Although the hamstrings are not thought to be affected by stretch weakness, it may be possible that the elongation of the muscle group in an individual with an anterior pelvic posture may be significant enough to produce a weakness in the muscle. However, Grossman et al. (1982) proposed that the "stretch weakness" phenomenon may depend on where in the range of motion the muscle's strength is tested. A muscle that has been continually elongated due to postural malalignment may actually be stronger at its 'new' length and weaker in a standard muscle testing position (Grossman et al, 1982).

Studies investigating the relationship between imposed muscle length and torque production of the hamstring muscles have found a linear relationship between hip angle and peak torque (Grossman et al., 1983; Grossman et al., 1984). These studies examined torque differences between subjects with long and short hamstrings. Tighter hamstrings were associated with larger magnitudes of force, regardless of imposed length. These results suggest that longer muscles may have less force production capabilities due to their elongated position, which is consistent with the clinical theories put forth by Kendall et al. (2005).

Kendall and colleagues (2005) believe hamstring weakness more commonly results in response to overstretching rather than lack of exercise. Overstretching may result in the weakening of a two-joint (or multi-joint) muscle that is exposed to repetitive movements or habitual positions that require elongation of the muscle beyond the normal range of muscle length (Kendall et al., 2005). Overstretching differs from 'stretch weakness' in that it requires the muscle to be stretched beyond the normal range of muscle length, and not necessarily for an extended amount of time. In conjunction with this theory, they also believe slight to moderate weakness of the gluteus maximus and hamstrings allow the pelvis to tilt anteriorly in the standing position. Therefore, according to this theory, overstretching of the hamstring muscle group may eventually lead to a weakening of the muscle group, which may then result in the adaptation of an anterior pelvic posture.

Genu Recurvatum

Genu recurvatum has been found to be associated with anterior pelvic tilt (Loudon, Jenkins, & Loudon, 1996; Hruska, 1998; Kendall et al, 2005). It has been proposed that an excessive anterior pelvic tilt creates a flexion moment at the hip, which is then counteracted with an extension moment at the knee (Kendall, 1983). The extension moment results in genu recurvatum, or hyperextension of the knee (Kendall, 1983). An additional explanation for the relationship between anterior pelvic tilt and genu recurvatum involves the idea that weakness of the medial and lateral hamstrings permits the knee to adapt a posture of genu recurvatum (Kendall et al, 2005). In other words, if in fact an anterior pelvic posture results in weakening of the hamstring muscle group, this may also have an influence on what is happening at the knee joint. Consequently, the combined affect of the anteriorly positioned pelvis moving the origin of the hamstrings superiorly, and genu recurvatum moving the insertion of the muscle group inferiorly, the hamstrings are placed at an even greater lengthened position, and therefore more susceptible to strength deficits (Kendall et al, 2005).

Measurement Issues

A variety of measurements will be collected and analyzed in an effort to answer the research question. The clinical measurements used in this study: pelvic inclination, hamstring extensibility, genu recurvatum, hip flexor tightness and hamstring strength, have previously been presented using many different techniques, and reliability of the measures are not always reported within the context of the study design. Therefore it is important to carefully consider the measurement techniques available to determine which methods are most appropriate and reliable.

Measurement of Pelvic Inclination

Pelvic inclination is typically determined using the anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS) of the ilium as marker placement. Although the same anatomical landmarks are used, a variety of techniques have been utilized by researchers to determine pelvic inclination, including computerized systems (Day et al., 1984; Spingle, Wootten, Bresler & Flinn, 2002), radiographs (Gajdosik, Simpson, Smith, & DonTigny, 1985; Spingle et al., 2002; Spingle et al., 2003; Kitajima, Mawatari, Aita, Shigematsu, Ogawa & Hotokebuchi, 2006), goniometers (Spingle et al., 2003), inclinometers (Pitkins & Pheasant, 1936; Walker et al., 1987; Heino et al., 1990; Crowell, Cummings, Walker & Tillman, 1994; Gilliam et al., 1994), and meter sticks with trigometric calculations (Sanders & Stavrakas 1981; Gajdosik et al., 1985; Alviso, Dong & Lentel, 1988). Pelvic inclination is most accurately measured using radiograph images, (Gajdosik et al., 1985; Spingle et al., 2002; Spingle et al., 2003; Kitajima et al., 2006) however; it is an expensive technique, potentially harmful and not always available and/ or practical for most clinicians. Therefore, clinically accessible measures will be the focus of this review.

Measures by Meter Stick

Pelvic inclination was determined in earlier studies using a meter stick-trigometric calculation method (Sanders and Stavrakas, 1981; Gajdosik et al., 1985; Alviso et al., 1988; Crowell et al., 1994). This technique involves using a meter stick mounted on a wooden platform with an attached, vertically adjustable sliding pointer. The height of the ASIS and PSIS from the floor is measured with the meter stick. A caliper is used to measure the distance between the ASIS and PSIS. Using these two values the angle of inclination of the pelvis is calculated using the following formula:

$$\text{Sin } \theta = \frac{\text{Side Opposite}}{\text{Hypotenuse}}$$

The hypotenuse is equal to the distance between the ASIS and PSIS as determined using the depth calipers. The height difference between the ASIS and PSIS represents the measurement for the side opposite.

This method was tested on twenty healthy men to determine same day intratester reliability ($r = 0.88$) (Gajdosik et al., 1985). Three years later this method was modified to determine inter-tester reliability; the modifications included adding a two point sight system to the adjustable sliding pointer mounted to the meter stick; foot tracings to standardize subjects' foot positions between testing sessions; and a palpation technique of palpate the bony landmark, mark and re-palpate (Alviso et al., 1988). These factors may have contributed to the improved reliability from r = 0.88 to r = 0.95. Currently, no studies could be found that have investigated the validity of this method of determining pelvic inclination. Although this method has proven to be reliable, the chief limitation is the time required to measure the angle of inclination. It was reported to take approximately ten minutes to collect pelvic inclination data of one side (Crowell et al., 1994).

Computerized Systems

The Iowa Anatomical Position System (IAPS) (Day et al., 1984) and Flock of Birds® (FOB) system (Spingle et al., 2002) are noninvasive computerized systems designed to statically assess and obtain coordinates for selected external anatomical landmarks. Although both methods of determining pelvic inclination are valid and reliable, these systems are also not readily available to clinicians and require considerable set up time in order to digitize the segments. Thus, while these methods of data collection are extremely useful and accurate, this mode of measurement is not cost effective for researchers solely interested in magnitude of anterior pelvic inclination.

Inclinometer

Researchers have more commonly used an inclinometer to directly determine the angle formed from the line between the anterior superior iliac spine and the posterior superior iliac spine and the horizontal plane (Pitkin & Pheasant, 1936; Walker et al., 1987; Heino et al., 1990; Gilliam et al., 1994). The inclinometer consists of a caliper with two arms which are placed over the subject's ASIS and PSIS, and the angle of pelvic tilt is then read from the gauge as the inclination of the PSIS relative to the ASIS in the horizontal plane (Pitkin & Pheasant, 1936; Walker et al., 1987). The idea of an inclinometer to determine pelvic inclination was first introduced by Pitkin and Pheasant (1936) and was later used to clinically measure spinal posture and motion (Loebl,1967).

Walker, Rothstein, Finucane and Lamb (1987) were the first to use an inclinometer to determine pelvic tilt, a method which has subsequently been used by others (Heino et al., 1990; Gilliam et al., 1994, Shultz, Nguyen, Windley, Kulas, Botic & Beynnon, 2006; Nguyen & Shultz, 2007). Pelvic tilt is measured by placing the arms of the inclinometer on the ASIS and PSIS, and recording the angle of inclination. The subject is asked to assume a normal standing posture with weight evenly distributed on both feet. To guarantee all measurements are collected in the same standing position, the subjects' feet can be traced for consistency between test sessions (Walker et al., 1987; Heino et al., 1990). Measurement of pelvic tilt using this method was found to have a high degree of reliability (ICC = .84), (Walker et al., 1987) when recorded by a single examiner, followed by a one-minute rest interval between re-measurement. The intratester reliability for this method of measuring pelvic tilt was also shown to be high in the study by Heino and colleagues (ICC = 0.83) (Heino et al., 1990). Other studies have attempted to determine both the intratester and interester reliability of this technique (Gilliam et al., 1994; Shultz et al, 2006). In one study three physical therapists were responsible for collecting data in this study. The intratester reliability values were ICC = 0.93, 0.96 and 0.96; and the interester reliability value was 0.95 (Gilliam et al., 1994). When the values for pelvic inclination obtained using the inclinometer were compared to the angles determined from radiographs, the results of this study failed to establish a significant level of validity. The researchers assumed the low correlation between the two methods implied that their measurements did not accurately reflect the pelvic angle based on the radiographic measurements (Gilliam et al., 1994). In other work comparing certified athletic trainers, with varying years of clinical experienced, lower reliability values (ICC) for those clinicians with less experience in the field were reported (Shultz et al., 2006).

Measuring Hamstring Extensibility

Muscle length cannot be measured and expressed as an absolute value in vivo (Toppenberg & Bullock, 1990); therefore, many different techniques have been developed in an effort to most accurately express muscle extensibility. Anatomical and mechanical factors such as bony blocks to movement, ligament extensibility, joint stiffness and pathological processes within the joint are unavoidable factors which may alter the maximum joint range of motion achieved when testing muscle length (Toppenberg & Bullock, 1990).

The straight leg raise (SLR) test has been commonly used to measure the length of the hamstring muscles (Gajdosik & Lusin, 1983; Toppenberg & Bullock, 1986; Toppenberg & Bullock, 1990; Gajdosik, Hatcher & Whitsell, 1992; Gajdosik, Albert & Mitman, 1994; Li, McClure, & Pratt, 1996; Mohamed, Perry & Hislop, 2002). This method of testing hamstring extensibility places the patient in the supine position with an inclinometer placed five centimeters below the inferior border of the patella in line with the tibia (Ekstrand et al., 1982; Li et al., 1996). The examiner maintains the knee joint in full extension with one hand while using the other to lift from the calcaneus and passively flex the hip. The leg is moved vertically until the subject first feels a stretching sensation in the posterior aspect of the thigh (hamstring), at which point the angle of inclination is read from the inclinometer. Neurological tissue is also stretched when performing this test and therefore may produce inaccurate results (Gajdosik & Lusin, 1983). The potential for posterior rotation of the pelvis during the test is an additional limitation of this method and consequently measurements may not be a valid indication of hamstring length (Bohannon, 1982; Gajdosik & Lusin, 1983).

A more reliable technique used to determine hamstring extensibility is the active-knee extension (AKE) test described by Gajdosik, and Lusin (1983). To perform this test the subject is positioned supine with the non-involved extremity secured to the table with a strap across the thigh. The involved thigh is held firmly against a vertical board or cross wire to maintain the hip at a 90 degree angle with the trunk (confirmed using a goniometer). An inclinometer is placed on the tibia, five centimeters below the inferior border of the patella (Li et al., 1996) or on the lateral aspect of the lower leg half way between the fibular head and lateral malleolus (Gajdosik & Lusin, 1983). While maintaining the hip at 90° and the ankle relaxed in plantar flexion, the subject actively extends the knee. The degree of knee extension, and thus hamstring extensibility, is read from the inclinometer at the first sign of mild resistance from the hamstring muscle group (Gajdosik & Lusin, 1983). The angle of active knee extension can also be determined reliably using a standard goniometer, by recording the angle formed between a line from the greater trochanter to the lateral joint line and a line from the lateral joint line to the lateral malleolus (Shultz et al, 2006). This method of measuring hamstring extensibility has been more commonly used in recent studies (Li e al., 1996; Nourbakhsh & Arab, 2002; Shultz et al, 2006).

Measuring Hip Flexor Extensibility

Although the hip flexors are not the primary muscle group of interest in this study, some research has shown it may be a confounding variable (Toppenberg, & Bullock, 1990; Nourbakhsh & Arab, 2002; Kendall et al., 2005), and therefore should be measured to rule out the possible effects of the hip flexors on pelvic tilt, hamstring extensibility and strength. The Thomas test, described by Kendall et al. (2005) has been used in previous studies to indirectly determine length of the hip flexor muscle group (Toppenberg & Bullock, 1990; Magee, 1992; Youdas et al., 1996; Nourbakhsh & Arab, 2002). The test is performed with the subject starting in a seated position at the end of the table with the thighs half on/off the table. The examiner then assists the subject into a supine position while the subject holds the posterior thigh of the non test leg, bringing it towards the chest while flexing the hip until the low back and sacrum are flattened on the table. Hip flexor tightness is then determined by the position of the other leg as determined using specific criteria (Kendall, et al., 2005; Shultz et al., 2006). Although clinically accepted, studies have not found the test to be impressively accurate, ICC = .50 (Youdas et al., 1996), and the validity of the test has not been established.

Measuring Hamstring Strength

Human skeletal muscle performance is best quantified isokinetically, and is an integral component of both clinical practice and research because it provides an objective assessment of muscle performance (Perrin, 1993; Wilk, Romaniello, Soscia, Arrigo, & Andrews, 1994; Keskula, Dowling, Davis, Finley, & Dell'omo, 1995; Chan & Maffulli, 1996; Iossifidou, Baltzopoulos, & Giakas, 2005; Sole et al., 2007). Isokinetic testing measures the rotational force or torque generated by a muscle against the lever arm at a constant rate of movement (Chan & Maffulli, 1996; Gaines & Talbot, 1999). Isokinetic testing requires a device know as a dynamometer, which allows the lever arm to move through a specified range of motion at a predetermined velocity and resistance increases as the subject increases the force applied against the dynamometer (Rothstein, Lamb & Mayhew, 1987; Perrin, 1993; Chan & Maffulli, 1996; Gaines & Talbot, 1999). As muscles are capable of producing different levels of torque at different angles in the range of motion, this mode of strength testing allows maximum resistance to be applied throughout the range of motion, which is not possible with isotonic or isometric strength testing (Perrin, 1993; Chan & Maffullli, 1996). This is an advantage over isotonic strength tests where the applied load is limited to that which can be moved or resisted at the weakest point in the range of motion. Because the dynamometer on an isokinetic strength testing device does not allow the limb to accelerate beyond the preset angular velocity, no resistance is provided until the limb exceeds the preset speed, at which time the dynamometer provides a counterforce of equal resistance to ensure a constant rate of movement (Rothstein, Lamb & Maythew, 1987; Perrin, 1993). Therefore, maximal effort is required to adequately examine muscle strength. Peak torque is commonly used to determine isokinetic muscular strength at the knee, and is defined as the maximum amount of rotational force or peak torque that can be generated by the muscles around the knee to flex and extend the joint (Gaines & Talbot, 1999). While peak torque can be calculated through a range of speeds and joint angles (Gaines & Talbot, 1999), angular velocities ranging from 60-180^{o}/sec are most commonly used to assess strength.

Validity

Torque measurements on isokinetic devices are referred to as "dynamic testing", and are related to an individuals functional capacity (Rothstein et al., 1987, Chan & Maffulli, 1996). This assumption comes from the concept that the subject's limb is moving during the test, therefore the measurements may appear to provide more meaningful indexes of function than isometric measurements (Rothstein et al., 1987). Several studies have explored the relationship between isokinetic strength and functional performance (Cordova, Ingersoll, Kovaleski, & Knight, 1995; Wu, Li, Maffulli, Chan, & Chan, 1997; Dowson, Nevill, Lakomy, Nevill & Hazeldine. 1998; Iossifidou et al., 2005;

Pua, Koh, & Teo, 2006). A continuous concentric-eccentric cycle is thought to reflect normal activities, such as walking and running (Wu et al., 1997). The peak torque generated by the quadriceps obtained at 90°/second and 180°/second has been shown to assess functional performance of the muscle group during concentric contractions (Pua et al., 2006), and at 240°/second during both concentric and eccentric contractions (Dowson et al., 1998). Studies have concluded isokinetic tests at greater velocities, between 180°/second and 300°/second, more accurately predict functional performance, when using squat landings (Iossifidou et al., 2005) and sprint time (Dowson et al., 1998), as an assessment of functional performance. Based on the literature, when the appropriate parameters are selected and procedures are followed, isokinetic strength can be a useful tool in assessing an individual's function strength.

Reliability

Isokinetic testing devices have been shown to be highly reliable in measuring isokinetic concentric and eccentric variables (Li, Wu, Maffulli, Chan, & Chan, 1996; Rothstein et al., 1987; Sole et al., 2007). A recent study indicated very high reliability for knee flexion (concentric ICC = .94, eccentric ICC = .92) and extension (concentric ICC = .95, eccentric ICC = .94) at a velocity of 60°/sec (Sole et al., 2007). Intertester reliability was established for isokinetic muscle performance of knee extension and flexion when clinicians with varying clinical experience followed the same standardized measurement protocol (Keskula et al., 1995). To ensure reliable and valid strength measures, it is critical that examiners use a consistent testing procedure (Iossifidou et al., 2005). Thus, several preliminary considerations must be accounted for when collecting strength information isokinetically. It is important to properly educate the subjects using a scripted set of instructions prior to the test, and this is especially true if the subject has never been tested using an isokinetic testing device (Perrin, 1993). The subjects should also have a consistent warm-up period with a preset level of intensity and duration, followed by practice trials prior to actual testing to allow the subject to familiarize him or herself with the testing technique (Perrin, 1993). When testing both concentric and eccentric contractions, it is critical to adequately familiarize the subject in the form of warm-up repetitions at the desired test velocities and contraction modes. The warm-up should consist of first submaximal, followed by maximal efforts (Perrin, 1993).

Summary

Anterior pelvic tilt is commonly regarded as an undesirable posture. Although this type of posture is associated with multiple negative clinical connotations, a lack of empirical evidence is available to clearly support these theories. It has been postulated that four muscle groups are responsible for the static orientation of the pelvis: erector spinae, abdominals, hip flexors, and hamstrings. Despite the clinical assumption that tightness or weakness of the muscles attaching to the pelvic affect the inclination of the pelvis, current research does not show a significant relationship between the strength and/or tightness of the abdominal muscle group or hip flexor muscle group in a relaxed standing position. Further, the assumption that anterior pelvic tilt is associated with weakened hamstring muscles (hip extensors) has not been adequately investigated.

According to biomechanical concepts, it is possible that there may be a relationship between the two variables. When the pelvis in tilted anteriorly, the origin of the hamstring muscle group is further away from the insertion, potentially placing the muscle in a lengthened and weakened position. As research has been shown that muscles cannot generate the same amount of torque when positioned in a lengthened position compared to a more shortened position, maintaining the hamstrings in a more lengthened position may result in hamstring weakness. Understanding these relationships are important, as a large body of literature supports the belief that lengthened and weakened hamstrings may predispose an athlete to lower extremity injuries, specifically hamstring strains and ACL injuries.

CHAPTER III

METHODS

Research Design

An experimental, within-subjects design was used to compare pelvic inclination, hamstring extensibility and hamstring strength. Among other variables, subjects were tested for pelvic inclination, hamstring extensibility, hip flexor tightness and genu recurvatum during a station-to-station preseason screening. In a separate test session, the strength of the hamstrings was determined using a Biodex isokinetic testing system. The independent variables in this study were hamstring extensibility and pelvic inclination and the dependent variable was hamstring strength. Hip flexor tightness and genu recurvatum were also accounted for as suppressor variables.

Participants

NCAA Division IAA Women's Volleyball, Women's Cross Country and Women's Soccer student-athletes from the University of North Carolina at Greensboro participated in this study. Participants were limited to only females to avoid other sex confounding factors that may influence strength (Campenella, Mattacola, & Kimura, 2000) and posture (Nguyen & Shultz, 2007). Although all student athletes at UNC-Greensboro are required to complete a comprehensive pre-participation physical examination and screening prior to intercollegiate athletic participation, only the fall female sports were analyzed. This resulted in a sample of 43 athletes, which power calculations confirm is sufficient to detect an R^2 value of .25, which represents a large effect. This criteria was considered acceptable since a large effect would be required to establish pelvic angle and hamstring extensibility as meaningful and accurate predictors of hamstring strength. Inclusion criteria were active status on the women's volleyball, women's cross country or women's soccer roster, and completion of the UNCG pre-participation physical examination, with clearance for full participation. Subjects were excluded if they had an incomplete pre-participation physical examination or were unable to complete any of the required tests and measurements (hamstring extensibility, pelvic angle, genu recurvatum, Thomas test, isokinetic testing). All subjects gave their informed consent to use their data obtained during the pre-season screening evaluation for research purposes by signing a consent form approved by the University of North Carolina at Greensboro Institutional Review Board.

Instrumentation

Pelvic inclination was determined using a pelvic inclinometer (Performance Attainment Associates, St. Paul, MN). Hamstring extensibility was measured using a bar mounted on a steel frame affixed to the table and a goniometer. The Thomas test was performed on a standard treatment table. Genu recurvatum was assessed using a four inch bolster and a goniometer. Isokinetic strength was assessed using a Biodex™ System 3 Pro isokinetic dynamometer (Biodex Medical Systems, Shirley, NY) and Biodex™ software (Rev. 2.15 Beta; Biodex Medical Systems, Shirley, NY).

Procedures

Overview

Prior to intercollegiate athletic participation, all student-athletes at the University of North Carolina at Greensboro were required to undergo a comprehensive pre-participation examination, which includes both general medical and orthopedic screens, and a station-by-station musculoskeletal risk factor screen to collect prospective data on various anatomical and functional measurements. The athlete screening took place in the Research Gymnasium in the University of North Carolina at Greensboro's Health and Human Performance Building. Prior to participation all student-athletes provided informed consent to use their pre-season screening data for research purposes. The student-athletes were randomly assigned to start at one of the 14 testing stations and then rotated through all the stations. Stations included assessment of lower limb anatomical alignment, joint laxity, hip strength, a sport psychology survey, balance testing, functional testing and kinematic analysis of landing. Within three weeks of the screenings, each subject reported to the University of North Carolina at Greensboro's Applied Neuromechanics Research Laboratory for isokinetic strength testing. While the subjects were participating in practice, conditioning and weight lifting sessions during the interval between testing; no significant strength gains were expected during this short time interval. The specific data extracted from the screenings for this study included: the bilateral values for pelvic angle, hamstring extensibility, hip flexor tightness (Thomas test), genu recurvatum, and concentric and eccentric hamstring peak torque. The procedures for collecting each variable follows.

Pelvic Inclination

Pelvic inclination was assessed in a standardized relaxed standing posture using a pelvic inclinometer (Performance Attainment Associates, St. Paul, MN). This technique has been demonstrated to be both reliable and valid (Gajdosik et al., 1985; Shultz et al., 2006). Standing erect, with feet shoulder width apart, the subject was asked to place her arms across her chest, while the inferior prominence of the anterior superior iliac spine (ASIS) and the most prominent portion of the posterior superior iliac spine (PSIS) were palpated. The calipers of the inclinometer were placed on the bony landmarks and the angle was measured to the nearest degree using the inclinometer (Shultz et al., 2006). Three measurements were taken on each subject and averaged for data analysis. A single examiner who has established excellent reliability on this measure (ICC = .98, SEM = 0.50) measured all subjects (Shultz et al., 2006).

Hamstring Extensibility

Hamstring extensibility was determined using the active-knee extension (AKE) test.(Gajdosik & Lusin, 1983; Shultz et al., 2006) The subject was positioned in supine on a table with the test hip flexed to 90^o and the contralateral hip placed at 0^o with the foot supported. A bar mounted on a steel frame affixed to the table served as a tactile cue for the subject to maintain her hip flexion at 90^o angle. The subject was then instructed to extend her knee as far as possible and hold that position for approximately two seconds. Prior to assessment, five practice trials were completed to reduce the effects of tissue extensibility/creep to obtain a more stable measure. If the subject was able to completely extend her knee, the same procedure was repeated with the hip in 120º of flexion. Prior to measurement, the anterior and posterior portions of the lateral joint line of the knee were palpated and the midpoint marked in the sagittal plane. With the axis of the goniometer placed over this mark, hamstring extensibility was measured using a standard goniometer as the angle formed between the stationary arm aligned with the greater trochanter, and the movable arm aligned with the lateral malleolus. The knee angle was measured to the nearest degree, with a larger angle indicating greater hamstring extensibility (Shultz et al., 2006). A single examiner with established reliability (ICC = .96, SEM = 2.26) measured hamstring extensibility on all subjects.

Thomas Test

Hip flexor tightness was assessed using the Thomas Test. The subject began seated at the end of the table with her mid thigh at the edge of the table. The examiner assisted the subject into a supine position while the subject held the posterior thigh of the non test leg and brought it towards the chest while flexing the hip. The thigh was pulled toward the chest only enough to flatten the low back and sacrum on the table, as verified by the examiner's hand placed under the lumbar spine. Hip flexor tightness was then determined by the position of the other leg and was recorded based on the following criteria: 1) the posterior thigh touched the table and the knee passively flexed approximately 80º or more – indicating no hip flexor or rectus femoris tightness, 2) the posterior thigh remained touching the table and the knee passively flexed less than 80º - indicating rectus femoris tightness, 3) the posterior thigh did not touch the table and the knee passively flexed approximately 80º - indicating hip flexor tightness, and 4) the posterior thigh did not touch the table and the knee passively flexed less than 80º. In the case of number four, the examiner passively extended the knee and evaluated whether the posterior thigh touches the table. If the posterior thigh dropped to the table when the knee was passively extended the subject was classified as having a tight rectus femoris. If the posterior thigh remained flexed off the table upon passive knee extension, the subject's hip flexors were determined to be tight.

As both the rectus femoris and hip flexors have the potential to influence the inclination of the pelvis in the same direction; the two variables were analyzed together and represent one variable, "anterior muscle tightness". This variable will account for the anterior musculature acting on the pelvis. If the subject had either hip flexor tightness or rectus femoris tightness (or both), their condition was coded as a (1), indicating anterior tightness, if the subject did not have tightness of the hip flexor or rectus femoris they were labeled as a (0), and classified as "normal", or no anterior musculature tightness as defined within this study.

Genu Recurvatum

Genu recurvatum was measured with the subject supine on a table. A small bolster (4 inches) was placed under the distal aspect of the tibia while the anterior and posterior portions of the lateral knee joint line were palpated and a mark placed at the midpoint in the sagittal plane. The most prominent aspect of the lateral malleolus and the greater trochanter was also palpated and marked. The subject was then instructed to actively contract her quadriceps and maximally extend her knee while the investigator aligned the goniometer for measurement. The axis of the goniometer was positioned over the mark on the joint line, and the angle formed by a line from the lateral joint line to the greater trochanter, and a line from the lateral joint line to the lateral malleolus was measured to the nearest degree with a standard goniometer (Shultz et al., 2006). A single examiner with established intratester reliability (ICC = .99 , SEM = .36) performed all measurements.

Isokinetic Testing

Isokinetic strength testing was performed using a Biodex™ System 3 Pro (Biodex Medical System, Shirley, NY) using a protocol established for all student-athletes at the University of North Carolina at Greensboro. The subjects were tested for concentric/eccentric knee extensor and knee flexor strength in a seated position. Prior to testing, the Biodex was properly positioned to the subject and settings were documented. Trunk, hip and thigh stabilization straps were first applied to stabilize the subject and allow maximum torque production (Magnusson, Geismar, Gleim & Nicholas, 1993). The seat angle was set at 85º. The seat length was then adjusted to align the distal end of the posterior thigh at the edge of the seat. The A-P position and height of the seat was adjusted to align the lateral femoral epicondyle to the axis of rotation of the lever arm; this landmark was marked to insure consistency. The distal end of the shank pads was positioned two centimeters above the malleoli. All chair and dynamometer head settings were recorded for future use. After the subject was properly positioned in the device, she was removed from the isokinetic dynamometer to complete a five minute warm-up on a cycle ergometer (LifeFitness 9500 HR, Sport Tiedje, Scheswig, Germany) with the level set at five. At the conclusion of the five minute warm-up the subject was repositioned in the Biodex.

For concentric/eccentric testing of the quadriceps muscle group, the range of motion (ROM) was set at 20° to 90° of knee flexion (Hamilton, 2006). The starting ROM of 90° was determined using a standard goniometer. Then limb and lever arm was then weighed at 30° of flexion. After the subject was properly stabilized and positioned in the Biodex, and the range of motion was set, she underwent a standardized isokinetic warm-up protocol prior to actual data collection. The protocol consisted of the four consecutive tests at increasing efforts. Subjects were first instructed to perform three repetitions at 25% effort, then three at 50%, followed by two repetitions at 75% and finally two at 100%. Fifteen seconds of rest was given between each warm-up set. Following the warm-up/familiarization the subject was given one minute of rest (Parcell, Sawyer, Tricoli & Chinevere, 2002) before completing five test repetitions. The knee extensor protocol consisted of a concentric/eccentric contraction sequence, with concentric contractions performed at an angular velocity of 180°/second and eccentric contractions performed at an angular velocity of 90°/second. The subject was instructed to cross her arms across her chest for the duration of the test. During the test repetitions, strong verbal encouragement was given to continually "kick as hard and fast as possible" during the knee extensor testing. Visual feedback was also provided, by allowing the subject to see the computer screen during testing. Upon completion of the five test repetitions on the right leg, the same procedure was conducted on the left leg.

The knee flexors were tested immediately following the knee extensors. The previously recorded settings were used to ensure proper subject position. The ROM for the knee flexors was set at 90° of knee flexion to full extension (0°), with the starting position of 90° confirmed with a standard goniometer. After the ROM was set the subject completed the same warm-up repetitions as performed during the knee extensor test. Once again the starting position of 90° was identified and the limb was weighed at 30° of flexion. The knee flexor protocol consisted of an eccentric/concentric contraction sequence, with the eccentric contraction performed at an angular velocity of 90°/second and concentric contractions performed at an angular velocity of 180°/second. The same cushion and torque limits were used as used for the knee extensors. The subject was instructed as before to cross her arms across her chest and given verbal encouragement to "pull as hard and fast as possible" during the testing. Visual feedback was also provided, by allowing the subject to see the computer screen during testing. Upon completion of the five test repetitions on the right leg, the same procedure was conducted on the left leg.

Due to the variability in the peak torque values the "windowed data" was used for analysis, as it only included data generated at or above the selected isokinetic test speed. Any data acquired at less than 70% of the pre-set isokinetic speed was eliminated from the display. This is a feature in the Biodex Software used to eliminate torque spikes generated at end range of motion stops.

Statistical Analyses

Hamstring extensibility (deg), pelvic angle (deg), anterior muscle tightness (0,1), genu recurvatum (deg) and hamstring concentric and eccentric peak torque were entered into an excel spreadsheet for each subject and then exported to SPSS version 15.1 (SPSS Inc., Chicago, IL) for analyses. Peak torque represented the greatest torque value across the entire range of motion in any one of the five trials, and was normalized to body mass and recorded in Newton-meters/kilogram (Nm/kg). To test the first hypothesis, a simple linear regression was used to determine if the amount of anterior pelvic tilt (independent variable) predicted the amount of hamstring extensibility (dependent variable). To test the second hypothesis and examine the relationship between anterior pelvic tilt, hamstring extensibility and hamstring strength, a step-wise multiple linear regression analysis was used to determine whether anterior pelvic angle and hamstring extensibility (independent variables) predicted the amount of hamstring muscle strength (dependent variable) once genu recurvatum and anterior muscle tightness were accounted for (suppressor variables). The alpha level for all analyses was set at $P \leq 0.05$.

CHAPTER IV

RESULTS

A total of 43 NCAA Division IAA female athletes (age = 19.2 ± 1.2 years, height = 168.5 ± 7.4 cm, weight = 63.0 ± 9.5 kg) completed this study; 14 volleyball players, 11 cross country runners, and 18 soccer players. Due to injury, two cross country runners were not included in the strength data collection, reducing the sample size to 41.

Table 1 provides the descriptive statistics by sport and the total sample for measurements of pelvic angle, hamstring extensibility, genu recurvatum, hip flexor tightness, rectus femoris tightness and anterior muscle tightness collected during the preseason screening. Table 2 provides the descriptive statistics for hamstring strength. The data from two subjects were excluded due to the inability to successfully complete the isokinetic strength testing as a result of previous injury, which decreases the total sample size from 43 to 41. Univariate ANOVAs revealed no significant differences in the independent or dependent variables across sports; therefore the entire sample was analyzed together.

Table 1. Means ± Standard Deviation and Range Statistics for left (L) and right (R) Pelvic Angle (PA, degrees), Hamstring Extensibility (HE, degrees), Genu Recurvatum (GR, degrees), Rectus Femoris Tightness (RF, 0 = not tight, 1 = tight), Hip Flexor Tightness (HF, = not tight, 1 = tight) and Anterior Muscle Tightness (AT, = not tight, 1 = tight)

	Volleyball Mean ± SD (N = 14)	Cross Country Mean ± SD (N = 11)	Soccer Mean ± SD (N = 18)	Total Sample Mean ± SD (N = 43)	Total Sample Range (N = 43)
PA_L	13.4 ± 3.5	15.2 ± 3.2	15.0 ± 4.3	14.5 ± 3.8	6.0 – 24.0
PA_R	13.8 ± 3.5	16.2 ± 3.0	16.6 ± 3.4	15.6 ± 3.5	9.0 – 23.0
HE_L	156.1 ± 9.4	151.3 ± 9.6	153.1 ± 13.6	153.6 ± 11.3	130.0 – 180.0
HE_R	154.8 ± 7.5	148.91 ± 9.9	152.2 ± 12.2	152.2 ± 10.3	128.7 – 170.7
GR_L	2.9 ± 3.2	2.5 ± 3.2	3.0 ± 2.9	2.9 ± 3.0	-4.0 – 10.0
GR_R	4.1 ± 3.3	4.2 ± 3.0	3.0 ± 2.8	3.7 ± 3.0	-1.7 – 10.3
RF_L	.7 ± .4	.9 ± .3	.8 ± .4	.8± .4	0.0 – 1.0
RF_R	.7 ± .4	.8 ± .4	.7 ± .5	.8 ± .4	0.0 – 1.0
HF_L	.07 ± .3	.09 ± .3	.06 ± .2	.07 ± .3	0.0 – 1.0
HF_R	.07 ± .3	.00 ± .00	.1 ± .3	.07 ± .3	0.0 – 1.0
AT_L	.8 ± .4	1.0 ± 0.0	.8 ± .4	.9 ± .4	0.0 – 1.0
AT_R	.9 ± .4	.8 ± .4	.8 ± .4	.8 ± .4	0.0 – 1.0

Table 2. Means ± Standard Deviation and Range Statistics for Left (L) and Right (R) Concentric (Con) and Eccentric (Ecc) Peak Torque Normalized to Body Mass (Nm/kg)

	Volleyball Mean ± SD (N = 14)	Cross Country Mean ± SD (N = 9)	Soccer Mean ± SD (N = 18)	Total Sample Mean ± SD (N = 41)	Total Sample Range (N = 41)
Con Ham_L	1.00 ± .58	.92 ± .45	.95 ± .43	.96 ± .48	.15 – 1.96
Con Ham_R	1.00 ± .55	.74 ± .25	1.00 ± .56	.94 ± .50	.11 – 2.11
Ecc Ham_L	1.94 ± .35	1.86 ± .31	2.03 ± .38	1.96 ± .35	1.08 – 2.83
Ecc Ham_R	1.95 ± .29	1.76 ± .42	2.05 ± .36	1.95 ± .36	1.06 – 2.62

Values are Nm/Kg

Hypothesis One

To test the first hypothesis, whether greater pelvic angle predicted greater hamstring extensibility, a simple linear regression analysis revealed no significant relationship between pelvic angle and hamstring extensibility on either the right (R = -.146, R^2 = .021, *P* = .175) or left (R= -.158, R^2 = .025, *P* = .156) sides. When genu recurvatum and anterior muscle tightness were also accounted for in the model, there was no change in the relationship between pelvic angle and hamstring extensibility on the left (Table 3a and b) or right (Table 4a and b) sides. However, on the left side, anterior muscle tightness entered the model first with the highest zero order correlation with hamstring extensibility (-.433), explaining 19.6% of the variance (P = .003). Genu recurvatum entered the model next, and explained an additional 2.7% of the variance, but this R^2 change was not significant (P = .248). For the right side, anterior muscle tightness entered the model first with the highest zero order correlation with hamstring extensibility (.209), but this only explained 4.4% of the variance, and was not a significant predictor (P = .179). In both cases looser anterior hip musculature was associated with greater hamstring extensibility.

Table 3a. Pearson Correlations for Variables Entered in Stepwise Regression Model when predicting hamstring extensibility based on pelvic angle, when accounting for anterior muscle tightness and genu recurvatum (Left)

	HE_L	PA_L	AT_L	GR_L
HE_L	1.00	-.158	-.433**	-.127
PA_L		1.00	.145	.050
AT_L			1.00	-.079
GR_L				1.00

**$P \leq 0.01$

Table 3b. Stepwise Regression Model Summary when Predicting Left Hamstring Extensibility

Model	R	R^2	Adjusted R^2	Standard Error of the Estimate	R^2 Change	F Change	df1	df2	Significant. F Change
1	.443[a]	.196	.177	10.258	.196	10.015	1	41	.003
2	.472[b]	.223	.184	10.211	.027	1.375	1	40	.248

a. Predictors: (Constant), Tight Anterior Muscles (L)
b. Predictors: (Constant), Tight Anterior Muscles (L), Genu Recurvatum (L)

Table 4a. Pearson Correlations for Variables Entered in Stepwise Regression Model when predicting hamstring extensibility based on pelvic angle, when accounting for anterior muscle tightness and genu recurvatum (Right)

	HE_R	PA_R	AT_R	GR_R
HE_R	1.00	-.146	-.209	-.067
PA_R		1.00	.029	-.072
AT_R			1.00	-.117
GR_R			-.012	1.00

Table 4b. Stepwise Regression Model Summary when Predicting Right Hamstring Extensibility

Model	R	R^2	Adjusted R^2	Standard Error of the Estimate	R^2 Change	F Change	df1	df2	Significant F Change
1	.209[a]	.044	.020	10.179	.044	1.872	1	41	.179
2	.251[b]	.063	.016	10.200	.020	.836	1	40	.366

a. Predictors: (Constant), Tight Anterior Muscles (R)
b. Predictors: (Constant), Tight Anterior Muscles (R), Pelvic Angle (R)

Hypothesis Two

To test the second hypothesis, whether increased pelvic angle and hamstring extensibility would predict decreased hamstring strength once controlling for anterior muscle tightness and genu recurvatum, separate multiple linear regressions were used to examine concentric and eccentric hamstring strength on the left and right sides. Tables 5a and 5b list the correlation coefficients and the regression model summary for predicting left hamstring concentric peak torque. These results revealed no significant relationships between the predictor variables and left concentric peak torque. Tables 6a and 6b list the correlation coefficients and the regression model summary for predicting right hamstring concentric peak torque. These results also revealed no significant relationships between pelvic angle and hamstring extensibility with right concentric peak torque. Genu recurvatum entered the model first, and explained 10.5% of the variance ($P < .05$). Anterior muscle tightness entered the model next, explaining an additional 7.3% of the variance (Significant F change = .074). Although hamstring extensibility and pelvic angle did not correlate with concentric hamstring strength on the right leg, less genu recurvatum ($r_{partial}$ = -.335) and more anterior muscle tightness ($r_{partial}$ = .285) were associated with increased concentric hamstring strength, but this was only significant on the right side.

Table 5a. Pearson Correlations for Variables Entered in Stepwise Regression Model for Left Concentric Hamstring Peak Torque

	PT/BW_{CL}	AT_L	GR_L	HE_L	PA_L
PT/BW_{CL}	1.00	.193	-.195	-.123	-.030
AT_L		1.00	-.080	-.443**	.145
GR_L			1.00	-.104	.022
HE_L				1.00	-.159
PA_L					1.00

**$P \leq 0.01$

Table 5b. Stepwise Regression Model Summary when Predicting Left Hamstring Concentric Peak Torque

Model	R	R^2	Adjusted R^2	Standard Error of the Estimate	R^2 Change	F Change	df1	df2	Significant F Change
1	.195[a]	.038	.013	.473	.038	1.537	1	39	.222
2	.263[b]	.069	.020	.471	.031	1.269	1	38	.267

a. Predictors: (Constant), Genu Recurvatum (L)
b. Predictors: (Constant), Genu Recurvatum (L), Tight Anterior Muscles (L)

Table 6a. Pearson Correlations for Variables Entered in Stepwise Regression Model for Right Concentric Hamstring Peak Torque

	PT/BW_{CR}	AT_R	GR_R	HE_R	PA_R
PT/BW_{CR}	1.00	.273	-.324*	-.020	.094
AT_R		1.00	-.012	-.209	.029
GR_R			1.00	-.051	-.076
HE_R				1.00	-.116
PA_R					1.00

*$P \leq 0.05$

Table 6b. Stepwise Regression Model Summary Predicting Right Hamstring Concentric Peak Torque

Model	R	R^2	Adjusted R^2	Standard Error of the Estimate	R^2 Change	F Change	df1	df2	Significant F Change
1	.324[a]	.105	.082	.484	.105	4.59	1	39	.039
2	.422[b]	.178	.135	.470	.073	3.369	1	38	.074

a. Predictors: (Constant), Genu Recurvatum (R)
b. Predictors: (Constant), Genu Recurvatum (R), Tight Anterior Muscles (R)

Tables 7a and 7b list the correlation coefficients and regression model summary for left hamstring eccentric peak torque. No significant relationships were found between the predictor variables and left eccentric peak torque. However, hamstring extensibility entered the model first, and explained 8.1% of the variance (Significant F Change = .075). Tight anterior muscle entered the model next, and explained an additional 2% of the variance (Significant F Change = .375). Although not significant, decreased hamstring extensibility ($r_{partial} = -.285$) was associated with greater eccentric peak torque on the left leg. Tables 8a and 8b list the correlation coefficients and the regression model summary for predicting right eccentric peak torque. These results revealed no significant relationships between the predictor variables and right eccentric peak torque.

Table 7a. Pearson Correlations for Variables Entered in Stepwise Regression Model for Left Eccentric Hamstring Peak Torque

	PT/BW_{EL}	AT_L	GR_L	HE_L	PA_L
PT/BW_{EL}	1.00	.250	.049	-.285	.068
AT_L		1.00	-.080	-.443**	.145
GR_L			1.00	-.089	.033
HE_L				1.00	-.181
PA_L					1.00

** $P \leq 0.01$

Table 7b. Stepwise Regression Model Summary when Predicting Left Eccentric Hamstring Peak Torque

Model	R	R^2	Adjusted R^2	Standard Error of the Estimate	R^2 Change	F Change	df1	df2	Significant F Change
1	.285[a]	.081	.057	.343	.081	3.358	1	38	.075
2	.317[b]	.101	.052	.344	.020	.805	1	37	.375

a. Predictors: (Constant), Hamstring Extensibility (L)
b. Predictors: (Constant), Hamstring Extensibility (L), Tight Anterior Muscles (L)

Table 8a. Pearson Correlations for Variables Entered in Stepwise Regression Model for Right Eccentric Hamstring Peak Torque

	PT/BW_{ER}	AT_R	GR_R	HE_R	PA_R
PT/BW_{ER}	1.00	.173	.148	-.007	.179
AT_R		1.00	-.012	-.209	.029
GR_R			1.00	-.009	-.035
HE_R				1.00	-.163
PA_R					1.00

Table 8b. Stepwise Regression Model Summary when Predicting Right Eccentric Hamstring Peak Torque

Model	R	R^2	Adjusted R^2	Standard Error of the Estimate	R^2 Change	F Change	df1	df2	Significant F Change
1	.179[a]	.032	.007	.358	.032	1.259	1	38	.269
2	.246[b]	.060	.010	.358	.028	1.116	1	37	.298
3	.293[c]	.086	.009	.358	.025	.992	1	36	.326

a. Predictors: (Constant), Pelvic Angle (R)

b. Predictors: (Constant), Pelvic Angle (R), Tight Anterior Muscles (R)

c. Predictors: (Constant), Pelvic Angle (R), Tight Anterior Muscles (R), Genu Recurvatum (R)

CHAPTER V

DISCUSSION

The results of this study failed to confirm a significant relationship between pelvic inclination, hamstring extensibility and hamstring muscle strength. Although these results do not support the proposed hypotheses, they are consistent with previous findings regarding the relationship between pelvic inclination and hamstring extensibility (Toppenberg & Bullock, 1986; Link et al., 1990; Gajdosik et al., 1992; Gajdosik et al., 1994; Li et al., 1996; Nourbakhsh & Arab, 2002; Congdon et al., 2005). However, we attempted to explore these relationships in more depth by also accounting for other possible contributing factors in this study, specifically genu recurvatum and anterior hip muscle tightness. However, despite accounting for these additional variables, the relationships remained insignificant.

Hypothesis One

The first hypothesis of this study was that an increased anterior pelvic tilt would be associated with increased hamstring extensibility. The predicted relationship was based on the anatomical orientation of the hamstrings and the muscle group's proximal attachment to the ischial tuberosity of the pelvis. Based on the findings of this study, it is apparent that the tension in the hamstring muscle group alone is not sufficient to alter the inclination of the pelvis.

The results of this study agree with other research revealing no correlation between postural alignment and muscle lengths (Toppenberg & Bullock, 1986; Heino, 1990; Li et al., 1996). The study by Li et al. (1996) focused on subjects with short hamstrings and found no relationship between the muscle group length and pelvic inclination. The study also investigated the effect of hamstring stretching on the length of the muscle group and standing posture (Li et al., 1996). The results showed an increase in hamstring muscle length in the stretching group; however they failed to find a relationship between increased muscle lengths and increased pelvic inclination (Li et al., 1996). While the researchers suggested a possible relationship may have been found if subjects with longer hamstring muscles were investigated (Li et al., 1996); our results over a range of hamstring extensibility and pelvic angles were consistent with their original findings. These findings considered along with others (Toppenberg & Bullock, 1986; Heino, 1990; Link et al., 1990; Gajdosik et al., 1992; Gajdosik et al., 1994; Li et al., 1996; Nourbakhsh & Arab, 2002; Congdon et al., 2005) do not support the assumptions proposed by Kendall et al. (2005) that individuals with "flat backs" or a decreased pelvic tilt in the standing position tend to have short hamstring muscles.

While there was no significant relationship between pelvic angle and hamstring extensibility; hamstring extensibility was significantly correlated in the negative direction with anterior muscle tightness. That is, individuals with less hamstring extensibility (i.e. tighter hamstring) presented with greater anterior hip muscles tightness, however, only on the left side. This relationship may be a function of the individuals in this study having general lower extremity muscle tightness. Most of the subjects were left leg dominant, which may explain why the relationship was only found on the left side. In this study, leg dominance was defined as the dominant stance leg. A possible explanation for this relationship may be that a stronger muscle is typically tighter; hence, the dominant leg may more often be found to be tighter. Because the nature of the Thomas Test results in a categorized score of yes (tight) and no (not tight) rather than a continuous variable, a greater frequency of tightness ratings on the left side may have effected results. Toppenberg and Bullock (1990) found similar results revealing a significant negative correlation between hamstring and rectus femoris muscle length indices bilaterally.

Although not statistically significant, a negative correlation was found between pelvic inclination and hamstring extensibility bilaterally. These results seem to further contradict the proposed rationale for the relationship between the two variables, as the rationale is based on the theory that an increased pelvic angle places the hamstrings in a more lengthened position. One potential explanation for these results may be that an increased pelvic inclination does in fact place the hamstrings on some degree of stretch, and therefore when testing the extensibility using the AKE test the muscle appears to be less extensible due to the preexisting tension on the muscle group. These findings are also consistent with a study by Toppenberg and Bullock (1986) who also reported a negative but not significant correlation between pelvic inclination and hamstring extensibility, and concluded that hamstring muscle length was not associated with pelvic inclination.

Toppenberg and Bullock (1986) measured the lengths of several other muscles in addition to the hamstrings, all of which had attachments on the pelvis (abdominals, lumbar erector spinae, illiopsoas, gluteal muscles, and rectus femoris) and revealed no significant association between any of these muscle lengths and pelvic inclination. In fact, these muscle lengths only accounted for approximately 5.2% of the variance of pelvic inclination (Toppenberg & Bullock, 1986). Conversely, when we accounted for other muscle lengths, we found a fairly consistent negative relationship between anterior muscle tightness and hamstring extensibility that was stronger on the left side.

Work by Li et al. (1996) provides another potential explanation for the lack of significant finding between hamstring extensibility and pelvic angle. When standing with the hips in a neutral position and the knees in extension, the hamstrings are likely not under tension (Li et al., 1996). As such, when pelvic tilt is measured in this standing position, the muscle length may not influence pelvic position (Li et al., 1996). Therefore, to further explore this relationship it may be beneficial to measure pelvic tilt when the hamstrings are under tension and have the potential to influence the position of the pelvis.

In summary, hamstring muscle length did not have a significant association with pelvic inclination, despite the fact that the muscle group attaches to the pelvis, and contraction of the muscle group is capable of changing the position of the pelvis in the sagittal plane (Martin, 1968; Toppenberg & Bullock, 1986; Link et al., 1990; Gajdosik, Hatcher, & Whitsell, 1992; Gajdosik, Albert & Mitman., 1994; Li et al., 1996; Congdon, Bohannon, & Tiberio, 2005; Kendall et al., 2005). Further, this relationship was not improved once accounting for genu recurvatum and anterior musculature tightness, both of which appear to be more likely candidates to alter the position of the pelvis (Kendall, 1983; Loudon, Jenkins, & Loudon, 1996; Hruska, 1998; Kendall et al, 2005).

Hypothesis Two

The second hypothesis of this study was that a greater angle of pelvic inclination and increased hamstring extensibility would be associated with decreased strength production of the hamstring muscle group after accounting for anterior muscle tightness and genu recurvatum. The second hypothesis was based on the rationale that an increase in anterior pelvic tilt places the hamstrings in a weakened and lengthened position, leading to reduced hamstring force production (Grossman et al., 1982; Grossman et al., 1983; Grossman et al., 1984, Janda,1993; Kendall et al., 2005).

Upon analysis of hamstring strength data it was revealed that no significant relationships were found between concentric or eccentric peak hamstring torque and the predictor variables on either the left or right sides. These results remained constant once accounting for genu recurvatum and anterior muscle tightness. Although insignificant, the direction of the relationship between peak hamstring torque (concentric and eccentric) and hamstring extensibility was consistent with the research hypothesis, in that lengthened hamstrings were found to be associated with weak hamstrings, however, not to the point of statistical significance. Further, this relationship did not appear to be a function of increased anterior pelvic tilt. Based on these findings the tension in the hamstrings does not appear to have an appreciable influence the force production of the muscle group.

Clinical Relevance

These results conflict with the popular clinical belief that short and tight hamstrings bring about a posterior pelvic tilt (Kendall et al., 2005). Based on the findings of the current study, the tension in the hamstrings do not appear to significantly alter the orientation of the pelvis in standing, suggesting that posture alone does not play a major role in hamstring function. This is further supported by a lack of relationship between pelvic angle and hamstring strength. Therefore, when evaluating pelvic inclination, it is important for clinicians to consider that pelvic posture is multifaceted, and multiple factors may be responsible for the degree of pelvic inclination. Therefore, correcting pelvic posture may not be as straight forward as altering muscle lengths. Moreover, correcting an anterior pelvic tilt may not be necessary if the goal or concern is to prevent the hamstrings from being placed in a weakened and lengthened position.

Limitations

Several limitations in this study may have contributed to the results. First, only 41 female subjects, from specific sports (volleyball, cross country and soccer) were used for this study. A larger sample size and a broader range of athletes may have provided different results. Second, hip flexor and rectus femoris tightness were combined as "anterior muscle tightness" and was not measured as a continuous variable; subjects were either classified as being "tight" or "not tight", based on the results of the Thomas test. Further, it should be noted that the majority of the subjects were classified as having tight anterior musculature. Thus, categorizing the tightness in this way made it impossible to distinguish the degree of tightness from subject to subject. If hip flexor and rectus femoris tightness could have been measured as a continuous variable, thus providing a more quantitative assessment of the actual length/tightness of the muscle, these relationships may have been further clarified.

Another limitation of this study was the Biodex protocol used to determine hamstring muscle strength. Most of the subjects had no history on the Biodex prior to the study; consequently, a large amount of familiarization was required. The protocol consisted of both concentric and eccentric isokinetic contractions. For the subjects who had no experience on the Biodex it was difficult for them to comprehend the eccentric component of the protocol. Despite a familiarization and warm-up session on the Biodex, many of the subjects were observed to perform the strength test with some hesitation or difficulty during actual testing. It is possible this may have created some increased variability in the strength measures. Knee extensor strength testing was performed prior to the knee flexors, which may have been beneficial because it allowed to subjects to adjust to how the Biodex operated and what it felt like. Therefore, future studies should consider allowing more time for familiarization prior to testing. Further, the right leg was tested first on all subjects, which for that reason, may explain why relationships were stronger on the left side (i.e. subjects had more time to get comfortable with the protocol). Another potential limitation associated with strength testing on the Biodex is the position in which the subjects were tested. The subjects were tested in the seated position, which is very different from the position of the pelvis and length of the hamstrings in standing. However, the purpose of this study was to examine the long term effects of postural difference, therefore it was expected that if a chronic weakening of the muscle had occurred this would be detectable in any position.

Future Research

These results suggest that additional factors, such as other muscle lengths, lumbo-sacral angles, postural awareness and/or motor programming may contribute to the position of the pelvis. This study did not account for measurements of lordosis, lumbo-sacral angle, hip anteversion, abdominal muscle length, or erector spinae length. In addition to measuring abdominal and erector spinae muscle lengths, a more quantitative measure of hip flexor and rectus femoris tightness may be more beneficial in future studies. Additional research investigating the influence of these factors on anterior pelvic tilt may provide further insight on the contributions of pelvic posture. Further, future studies examining isokinetic strength should insure a more lengthy and complete familiarization to the testing protocol.

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