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Patellofemoral pain syndrome (PFPS), or pain in the area of the kneecap, has been diagnosed in as many as one in four patients seen at a sports medicine clinic, yet its etiology and risk factors are surprisingly not well understood (Devereaux & Lachmann, 1984). Lack of consensus in the literature suggests that the cause of PFPS is multifactorial, and in fact the etiology may be dependent on individual patients. One of the commonly studied risk factors for developing patellofemoral pain syndrome is overpronation at the subtalar joint. Patients with PFPS have been observed to have less dorsiflexion range of motion as compared to healthy individuals, though the topic has not been thoroughly investigated (Piva, Goodnite, & Childs, 2005; Witrouw, Lysens, & Bellemans, 2000). Compensatory pronation due to tightness of the plantar flexors may translate proximally into movement at the knee as the body continues to absorb the shock of landing, especially during running. Therefore, the purpose of this study was to examine how dorsiflexion range of motion (DFROM) is related to movement at the knee in the transverse, sagittal, and frontal planes. DFROM was measured during a weight-bearing lunge. Initial, peak, and excursion values for the ankle, knee and hip was calculated during the initial phase of a drop jump landing, as well as maximum joint moments, stiffness, and energy absorption for extensors of the lower extremity. Pearson product-moment correlations determined relationships between DFROM and ankle, knee, and hip kinetics and kinematics. Results showed positive correlations between dorsiflexion range of motion and peak ankle and knee flexion (Ankle: $r = .637$, $p = .003$;

Knee: $r = .604$, $p =.006$), as well as knee flexion and hip flexion excursion (Knee: $r = .634$, $p=.004$; Hip: $r = .461$, $p = .047$) No significant correlations were seen in any other planes. No correlations were seen with joint moments or stiffness values, but there was a significant correlation between DFROM and knee and hip energy absorption (Knee: $r = -.456$, $p = .049$; Hip: $r = -.524$ $p = .021$). These results support the idea that ankle dorsiflexion range of motion is related to proximal biomechanics, however the effects are limited to the sagittal plane. Those with lower values of dorsiflexion range of motion appear to have a propensity toward a “harsher” landing, which may increase their risk for sustaining both overuse and acute injuries.

EFFECT OF ANKLE DORSIFLEXION RANGE OF MOTION ON KNEE BIOMECHANICS: IMPLICATIONS FOR PATELLOFEMORAL PAIN SYNDROME

by

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APPROVAL PAGE

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TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

CHAPTER I

INTRODUCTION

Patellofemoral pain syndrome (PFPS) is one of the most common conditions affecting active individuals. PFPS has been estimated to affect as many as 56% of the active population (Thijs, Clercq, Roosen, & Witrouw, 2008), with females more than twice as likely to develop the condition as males (Boling et al., 2010). In addition, PFPS is most often seen in a younger population, with one study reporting that 70% of PFPS cases occurred in patients aged 16-25 years (DeHaven & Lintner, 1986). While PFPS affects athletes in a multitude of sports, including football, basketball, soccer, and baseball, it is particularly common in runners (DeHaven & Lintner, 1986). In a prospective study by Thijis et al. (2008), anterior knee pain was the most common complaint of runners (17% of 102 runners), followed by shin splints (11%), and Achilles tendon overuse (10%). Maughan & Miller (1983) found anterior knee pain was at least twice as prevalent in runners training for a marathon than any other injuries.

PFPS is a complex diagnosis, as it consists of a multitude of symptoms. These symptoms are highly variable between patients, and not all PFPS patients experience their pain in the same way. Patients with PFPS will often describe pain at or behind the patella during any of the following activities: going up or down stairs, squatting, kneeling, prolonged sitting, and during or after any physical activity (Bazett-Jones et al., 2013). Patients also will likely feel pain when the patella is manually compressed on the femur, when performing knee extension, and when palpating the lateral or medial borders of the patella (Bazett-Jones et al., 2013; Duffey, Martin, Cannon, Craven, & Messier, 2000; Thijs et al., 2008). Because the origin of this pain is thought to be multifactorial (Powers, Bolgla, Callaghan, Collins, & Sheehan, 2012), it is not surprising that the pain does not behave the same way in all patients with PFPS. The etiology of the pain differs on a case-by-case basis. Due to this, it is necessary to investigate all possible causes for PFPS.

While dysfunction at the hip may translate into altered distal kinematics, the opposite it also true. Currently, it is theorized that PFPS can arise from dysfunctions at either the proximal or distal segments of the lower kinetic chain. Proximally, hip abductor muscle weakness is considered to play a role in creating instability at the knee joint (Bolgla, Malone, Umberger, & Uhl, 2011). If the hip is unable to stabilize the lower leg during the stance phase of gait, kinetic and kinematic alterations will be seen farther down the kinetic chain at the knee (Prins & van der Wurff, 2009).

Movements of the foot and ankle can also affect motion at the knee (Barton, Levinger, Crossley, Webster, & Menz, 2012). In activities that include running or jumping, the foot is the first point of contact the body has with the ground. Any movement that occurs at the foot and ankle will then be translated to the knee via the tibia (McClay & Manal, 1997). One of the often-studied distal movements theorized to cause PFPS is pronation of the subtalar joint. Pronation is a tri-planar movement that includes dorsiflexion, eversion and abduction of the foot. Many studies have examined eversion characteristics of PFPS patients, but the dorsiflexion aspect of the movement has only recently been shown to be a possible risk factor (Piva et al., 2005; Witrouw et al., 2000). Manipulations of dorsiflexion ROM have been shown to directly influence dynamic knee valgus movements in healthy individuals. In a study by Macrum et al. (2012), restricting dorsiflexion was shown to increase medial knee displacement in young healthy adults. Conversely, when available dorsiflexion ROM is increased, medial knee displacement is thought to decrease (Bell, Padua, & Clark, 2008). However, it has yet to be established how natural variations in DFROM affect tri-planar movements at the knee, as many of the past studies have manipulated ankle ROM through artificial means.

Objective and Hypothesis

Since the relationship between natural amounts of dorsiflexion ROM and movement at the knee is unknown, it is important to first examine movement patterns in a healthy population before characterizing these relationships in a PFPS population. Therefore, the purpose of this study is to examine three-dimensional knee kinematics and kinetics in subjects with varying amounts of ankle dorsiflexion ROM. Determining the extent to which the amount of dorsiflexion may affect knee movement patterns may help inform treatment strategies targeting the flexibility of the plantar flexor muscle group.

It is hypothesized that if dorsiflexion range of motion is functionally restricted, subjects will show a greater amount of tibial internal rotation, knee valgus, and knee flexion. It also is hypothesized that those with greater amounts of dorsiflexion range of motion will better dissipate landing forces as evidenced by lower joint moments at the knee, hip, and ankle.

Assumptions and Limitations

1. Static weight-bearing dorsiflexion range of motion is comparable to that experienced during gait.
2. Results will only be representative of healthy, college-aged females, and cannot be generalized to other populations.
3. A bilateral drop-jump landing in a laboratory setting is representative of landings while running, or during landing in typical sporting events.

Delimitations

1. The study will be limited to data already collected as part of a larger biomechanical research project.
2. All subjects wore a standardized lab shoe for the drop jump procedure.
3. Only participants who were apparently healthy with no current ligament injury or recent lower extremity injury, and no known medical conditions affecting the connective tissues, vestibular system or balance ability, were included.
4. Only participants who had not participated in a strength training intervention for the past 3 months were included.
5. Data were only collected on subjects' left legs.

Operational Definitions

<u>Dorsiflexion Range of Motion (DFROM)</u>: The amount of available range of motion in the sagittal plane of the ankle joint during a weight bearing, forward lunge.

Drop Jump Landing: the first landing subsequent to falling off a 45 cm box, and prior to completing a second jump.

Initial Landing Phase: The phase of the drop jump landing beginning at the point of initial foot contact with the ground (vertical ground reaction forces >10 N) and ending at peak center of mass (COM) displacement.

Predictor Variable

DFROM: The amount of dorsiflexion the left ankle joint is able to achieve while performing a weight-bearing lunge.

Dependent Variables

Joint Excursion: The amount of joint motion the participant went through during the initial landing phase of a drop jump as calculated from the PEAK-INITIAL angles, calculated for ankle flexion, knee flexion, hip flexion, knee rotation, knee varus/valgus, and hip rotation.

Internal Joint Moment: The internal moment occurring about the joint in the sagittal plane ($Nm \cdot N^{-1} \cdot m^{-1}$). Calculated for the ankle, knee, and hip.

Joint Stiffness: The change in normalized net internal extensor moment divided by sagittal joint excursion (degrees) from initial contact to peak flexion excursion during the initial landing phase ($Nm \cdot N^{-1} \cdot m^{-1} \cdot degrees^{-1}$) calculated for the ankle, knee, and hip.

Sagittal Plane Joint Absorption: The integral of the negative phase of the joint power curve ($J \cdot N^{-1} \cdot m^{-1}$) from initial contact to peak flexion excursion where power is the product of the joint moment and joint angular velocity at each time point.

CHAPTER II

REVIEW OF LITERATURE

As obesity and overweight health issues become increasingly prevalent in society, more adults are turning to recreational running as a form of exercise (Buist et al., 2010). Running as a hobby is fairly inexpensive: memberships to gyms or clubs are not necessary, and there is no special equipment needed. Despite the health benefits, running can lead to both overuse and acute injuries. Incidence of lower extremity injuries in runners has ranged from 20-80%, with knee injuries accounting for 7-50% of these injuries (van Gent et al., 2007). Since running is a series of repetitive movements, chronic injuries are more common (Ferber, Hreljac, & Kendall, 2009). In a study of 2,002 runners, the most common injuries were patellofemoral pain syndrome (PFPS), iliotibial band friction syndrome (ITBFS), plantar fasciitis, meniscal injuries, and tibial stress syndrome. Among these runners, 331 presented at a sports medicine clinic over a period of 2 years with the diagnosis of PFPS. Of these, 207 (62%) were females, and most were relatively young (average age of 32.2 years at the time of diagnosis) (Taunton et al., 2002). Given this prevalence of PFPS in runners, it is important to understand the causative factors in order to prevent injuries from occurring and allow runners to remain active and gain the intended health benefits. Therefore, the purpose of this review is to explore what is currently known about risk factors for developing patellofemoral pain syndrome, addressing both intrinsic and extrinsic factors, and proximal, local, and distal risk factors, ultimately focusing on the role dorsiflexion range of motion has on tri-planar knee movement.

Patellofemoral Pain Syndrome

PFPS is broadly defined as "pain at or behind the patella" and has also been generalized as simply "anterior knee pain" (Witrouw et al., 2000). As a syndrome, patellofemoral pain may not manifest itself the same in all patients, and it is likely that it may present very differently in different populations. Much of the pain experienced by patients is during exertion, such as running, jumping/landing, squatting, kneeling, stair ascent/descent, and other exertional activities of daily living (Barton, Bonanno, Levinger, & Menz, 2010). Patients may also experience pain after sitting with flexed knees for a long period of time (Barton et al., 2010). Patellofemoral pain can also be provoked as a diagnostic tool. Pain may be felt with palpation of either the medial or lateral patellar facets or the anterior portion of the femoral condyles (Boling, Padua, Marshall, et al., 2009). Isometric quadriceps contraction at 30° of knee flexion may also create pain in those with PFPS due to compression of the patella in the trochlear groove (Barton et al., 2010).

Overview of Causes

The development of patellofemoral pain syndrome in runners may depend on any number of factors. It is commonly accepted that development of the syndrome is a combination of both intrinsic and extrinsic precipitating factors. However, the relationship between different factors is still in question (Messier et al., 1991; Pappas & Wong-Tom, 2012). In addition, PFPS sufferers may behave differently pre- and/or post-injury, making it difficult to determine which movement patterns are a cause or result of PFPS (Barton, Levinger, Menz, & Webster, 2009). Before determining cause and effect, it is important to distinguish where the greatest movement differences or dysfunctions occur, due to the fact that a combination of variables across different joints may combine to have similar affects on the patellofemoral joint. From this perspective, the knee cannot be looked at in isolation, since the body moves and works as a whole. For example, one patient may develop adverse compressive forces at the patellofemoral joint due to dysfunctions at the foot, while pain may be due to proximal muscle weakness in another. Because of the number of potential risk factors that may play a part in the development of PFPS, it is important to consider and examine each of them thoroughly. Understanding the effects of these variables on knee mechanics will help identify which factors could play the greatest part in development of this syndrome. In turn, this will lead the way to determining what treatments or preventive strategies may be most effective.

Extrinsic Risk Factors

Extrinsic risk factors are those that have to do with behaviors of the runner. These are often highly modifiable, and may vary greatly throughout a runner's training. Extrinsic risk factors focus on what the runner may do that incidentally causes them pain. These risk factors include excessive training, running surface, and choice of footwear while running (Messier et al., 1991).

Excessive Exercise

One of the most prominent risks for developing patellofemoral pain syndrome is excessive exercise. Runners who ran greater than 30 miles per week or more than 5 days per week were seen to have increased prevalence of lower extremity injury (Jacobs & Berson, 1986). It must be noted that increases in training alone should not cause injury (Figure 1). Rather, when combined with intrinsic factors, this increase in activity may cause any underlying dysfunctions to manifest and lead to pain (Messier et al., 1991).

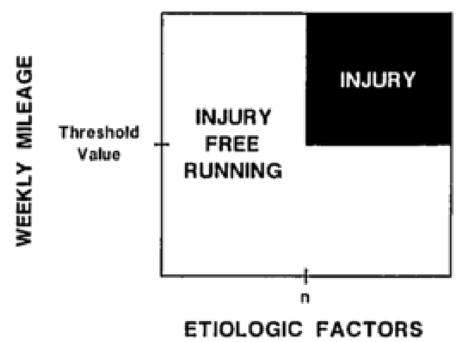

Figure 1. Theoretical Representation of Interaction Between Weekly Mileage and Etiologic Factors in Development of Overuse Running Injuries (Messier, Davis, & Curl, 1991)

Training Surface

It has been theorized that the surface that runners typically train on may contribute to development of injury, though there is no evidence to support this (van Gent et al., 2007). In one retrospective study, the development of PFPS had no relationship when training on asphalt or concrete when compared to softer trails or a track (Jacobs & Berson, 1986). Another retrospective study found injured and healthy control subjects to have no difference in their training surfaces, with the majority of both injured and uninjured runners training predominately on asphalt (Duffey et al., 2000).

Footwear

Within the running community, emphasis is placed on choosing the proper shoe to prevent pain or injury, although the literature has not identified improper footwear as a risk factor to injuries. One study compared injury incidence in subjects who were either assigned a shoe based on their plantar surface area or placed in a stability-type shoe regardless of foot type (Knapik et al., 2010). Plantar surface area is a common way for runners to be recommended for different shoe types. They found that both groups had similar injury rates during basic training for the United States Air Force, which relies heavily on running. Another study that randomly placed participants into a shoe regardless of their foot type saw that those placed in a motion control shoe (intended for those with extremely low foot arch heights) had a greater amount of running-related pain than those in either a neutral or stability shoe which are recommended for high or normal arch heights (Ryan, Valiant, McDonald, & Taunton, 2011). The authors also reported that those placed in their recommended shoe category did not necessarily experience less running-related pain than those who were placed in a seemingly incorrect shoe category.

In recent years, there has been an increased focus on barefoot or barefoot-style (minimalist) running. This is based on the theory presented by Lieberman et al (2010) that early runners did not use the heavily cushioned footwear seen today, and that it is unnecessary and possibly even harmful to runners. Patellofemoral joint stresses are reported to be lower in barefoot running, though effects on injury rates have yet to be prospectively studied (Bonacci, Vicenzino, Spratford, & Collins, 2013; Sinclair, Hobbs, Currigan, & Taylor, 2013).

Intrinsic Risk Factors

Intrinsic risk factors, or factors from within the body, may be classified in a number of ways. For purposes of this study, they will be discussed as proximal, distal, or local factors. Factors can also be discussed in terms of being modifiable or non-modifiable. Intrinsic risk factors are generally anatomical, physiological, or a combination of both (Witrouw et al., 2000). In the current study, particular focus will be placed on the distal risk factors of excessive pronation and limited dorsiflexion.

Global

A global intrinsic risk factor that is non-modifiable is gender. Females are 2 times more likely than males to have patellofemoral pain syndrome (DeHaven & Lintner, 1986; Taunton et al., 2002).This may be due to a multitude of intrinsic factors that differ between males and females, including excessive dynamic knee valgus, excessive contralateral pelvic drop, and greater internal rotation of the femur (Willy, Manal, Witvrouw, & Davis, 2012). Interestingly, many of these same factors have been proposed as potential risk factors for development of PFPS.

Psychological

Psychological variables have also been seen to affect both the development and recovery of patients with PFPS. Individuals who have inadequate coping mechanisms to deal with pain may be more likely to ruminate on the effects of their physical pain, causing it to seem more disruptive than in others (Witrouw et al., 2000). Patients with PFPS are seen to have lower self-perceived overall health than control subjects, and they have higher levels of mental distress (Jensen, Hystad, & Baerheim, 2005). These results suggest that even though symptoms are physical in nature, they may have effects on patients' overall psychological well-being.

Proximal Risk Factors

The quadriceps angle, or Q-angle, has been considered to be extremely important in development of pain at the patellofemoral joint. This angle is thought to represent the forces acting on the patella by the quadriceps muscle and patellar tendon (Powers, 2003). The Q-angle is the angle formed at the patella by (1) a line from the anterior superior iliac spine (ASIS) to the midpoint of the patella and (2) an extended line from the tibial tuberosity through the midpoint of the patella (Figure 2). This angle is increased in women as opposed to men due to the anatomical widening of the hips (Herrington & Nester, 2004).

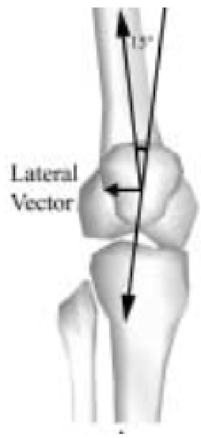

Figure 2. Measurement of the Q-angle (Powers, 2003).

Though there is some inconsistency in the literature regarding the impact the Q-angle has on patellofemoral pain, it is continually considered relevant in both diagnosis and evaluation (Caylor, Fites, & Worrell, 1993; Hamill, van Emmerik, Heiderscheit, & Li, 1999; Rauh, Koepsell, Rivara, Rice, & Margherita, 2007). Higher Q-angles are considered to be problematic as they may increase lateral forces at the patellofemoral joint (Mizuno et al., 2001). Q-angles are primarily determined by a patient's anatomy, but the angle can be affected by rotation of specific joint segments. In cadavers, when the tibia was rotated internally, the Q angle decreased, but the position of the patella changed to create greater lateral forces in the joint (Mizuno et al., 2001). Internal rotation of the femur can increase the Q-angle by allowing the patella to move medially in comparison to the stationary ASIS. In both cases, the patella is being pulled by the lateral retinaculum. This dense tissue resists the medial movements the patella is making, and contributes to create greater forces on the lateral surface of the femur (Powers, 2003).

One of the most often studied proximal risk factors that may contribute to excessive Q-angle is weakness at the hip joint. Specifically, weakness of the hip abductor muscles is thought to be a main contributor to development of patellofemoral pain syndrome. If the abductor muscles are weakened, then the body cannot stabilize the hip appropriately and this in turn creates an abnormally high dynamic Q-angle due to excessive internal rotation at the femur (Powers, 2003; Prins & van der Wurff, 2009). In the stance phase of running, the hip musculature must be able to align the body and coordinate movements between the lower extremity and the trunk. If a runner has insufficient hip strength, they may not be able to adequately support the rest of the body or maintain postural alignment (Powers, 2010). Excessive or poorly coordinated motion will be transferred down the kinetic chain from the hips, and may exert abnormal pressure within the patellofemoral joint (Powers, 2010).

In support of this theory, multiple cross-sectional studies have often seen patients with patellofemoral pain to have weakened hip musculature when compared to healthy controls (Bolgla et al., 2011; Boling, Padua, & Creighton, 2009; Cichanowski, Schmitt, Johnson, & Niemuth, 2007; Piva et al., 2005; Robinson, 2007). There only has been one prospective study to analyze this, and the researchers found that those who developed PFPS had less hip abduction strength than those who did not, yet there were no differences seen in other movements (Boling, Padua, Marshall, et al., 2009). One study found PFPS patients to have slightly less abduction strength, but did not report it as being significantly less than the control group (Piva et al., 2005). Another study found the hips in the symptomatic legs of PFPS patients to be significantly weaker than healthy controls in flexion, extension, abduction, internal and external rotation (Cichanowski et al., 2007). When compared to their own asymptomatic limbs, strength deficits were seen only in abduction and external rotation. Similar results were found by Robinson & Nee (2007), though they found that subjects also had less hip extension strength when compared to their asymptomatic limb. Interestingly, they did not find a difference in abduction strength between controls and symptomatic patients, though the data trended toward less strength in the PFPS group (Robinson, 2007). Another study that compared PFPS patients to controls also found the symptomatic patients to have decreased abductor and external rotation strength, but no differences in extensor strength (Boling, Padua, & Creighton, 2009). Together, these studies suggest that those with PFPS may have weakened hip musculature. The extent to which this weakness influences the development of PFPS is yet to be determined in prospective studies. However, it has been shown that during an exhaustive run, greater hip adduction angles were present in those PFPS patients with less strength (Dierks, Manal, Hamill, & Davis, 2008).

Local Risk Factors

Local risk factors for developing PFPS include anatomical abnormalities and weakness of muscle groups surrounding the patellofemoral joint. Anatomical risk factors may play a large part in the localized pain felt by patients. The specific anatomy of the femoral trochlea and patellar surface is important as it can alter the area of contact forces felt at the patella (Amis, 2007). Other anatomical characteristics, including torsion of the tibia or femur or tightness of the medial or lateral retinaculum may contribute to maltracking of the patella in the trochlea, causing increased force on the underlying articular cartilage (Amis, 2007; Noehren, Barrance, Pohl, & Davis, 2012).

Weakness of the quadriceps muscle group has also been implicated in development of patellofemoral pain (Toumi et al., 2013), though it is unclear whether weakness or delayed muscular activation is the problem. In a number of studies, the strength of quadriceps muscles of PFPS patients was found to be lower as compared to pain-free controls in multiple studies (Bolgla et al., 2011; Piva et al., 2009; Witrouw et al., 2000), however others have reported no strength differences (Duffey et al., 2000; Messier et al., 1991).

Weakness in the vastus medialis obliquus (VMO) is thought to significantly contribute to irregular tracking of the patella (Amis, 2007). The VMO functions to medially stabilize the patella. If the muscle is weakened, the patella may be pulled laterally, creating increased pressure on the lateral facet of the femur. This weakness may exacerbate any underlying anatomical or other physiological factors (Waryasz & McDermott, 2008). Witrouw et al. (2000) found in a prospective study that subjects who developed PFPS had faster response times in their VMO and vastus lateralis (VL) than controls who did not, which may cause imbalances in frontal plane stresses at the patellofemoral joint. Another study examined the activation patterns of the VMO as compared to the VL in both patellofemoral pain patients and healthy controls while going down steps (Cowan, Bennell, Hodges, Crossley, & McConnell, 2001). They found that in the symptomatic PFPS patients, the VL was activated followed by the VMO, yet activation occurred simultaneously in healthy control subjects. The results of these two studies indicate that uneven timing of the VMO and the VL may be more important than the strength of these muscles in development of PFPS due to uneven dispersion of forces across the joint surface.

Distal Risk Factors

Distal risk factors for patellofemoral pain typically include dysfunctions at the foot and ankle, including excessive rearfoot eversion, reduced dorsiflexion, static foot posture, and greater midfoot mobility. For this review, the focus will be on pronation because it is an often implicated, but not well understood factor in the development of PFPS. Simply put, pronation is a tri-planar movement at the subtalar joint consisting of eversion, abduction, and dorsiflexion. While pronation has been studied extensively in the literature, no consensus can be found on the role it plays in patellofemoral pain syndrome. The extent to which subjects with patellofemoral pain exhibit overpronation in cross-sectional studies is questionable, as multiple studies have found no difference in measures of pronation between PFPS patients and controls (Duffey et al., 2000; Levinger & Gilleard, 2007; Messier et al., 1991; Powers & Chen, 2002).

Still, subtalar pronation may be important to consider in the overall injury risk equation, as movement dysfunctions that occur at the foot and ankle complex may translate up the kinetic chain to the knee through the tibia, possibly creating excessive pressure at the patellofemoral joint. An increase in lateral stress at the patellofemoral joint has been shown to contribute to the development of PFPS (Myer et al., 2010). By breaking down the movements involved with pronation, we may be able to determine what kinematics are occurring at the knee to result in abnormal patellofemoral positioning or forces (Figure 3).

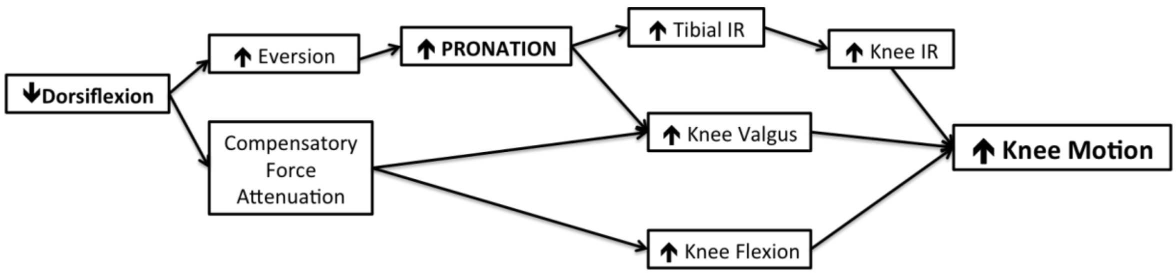

Figure 3. Progression of Distal Factors Into Movement at the Knee

Pronation Pronation is a complex movement which occurs in all three planes of motion. By combining ankle eversion, dorsiflexion, and foot abduction, pronation serves to allow the foot and ankle complex to absorb shock and dissipate a portion of the forces of gait (Rockar, 1995). When the foot comes in contact with the ground during gait, it is in a slightly supinated position, then pronates to absorb shock, then again supinates in order to push off. As the talus rotates in the transverse plane, the tibia must move concurrently due to the anatomical shape of the bones. The tibia will internally rotate, and theoretically proximal segments of the leg will move with it (Tiberio, 1987). When the tibia internally rotates, the patella will attempt to medially move and tilt, but lateral structures in the knee will prevent this: causing greater stresses on the lateral facet of the femur (Mizuno et al., 2001). In theory, a greater valgus position at the knee will create greater forces through the patellofemoral joint. If movement is isolated to the frontal plane, when the rearfoot is everted, the knee follows it medially into a valgus position.

Pronation is often generalized by measuring navicular drop. By measuring how much the navicular bone moves vertically when going from a neutral to a weight bearing position, it is assumed to be concurrent with the amount of available pronation (Menz, 1998). While this value is thought to measure pronation as a whole, it likely places large weight on the eversion of the joint. Studies have shown that PFPS subjects have greater navicular drop values than controls (McPoil, Warren, Vicenzino, & Cornwall, 2011; Mølgaard, Rathleff, & Simonsen, 2011), and that subjects with higher navicular drop values are more likely to develop PFPS (Boling, Padua, Marshall, et al., 2009), as well as have valgus knee positioning (Joseph et al., 2008; Mizuno et al., 2001).

Eversion Greater values of peak rearfoot eversion are correlated with peak tibial internal rotation in patellofemoral patients when compared to controls (Barton et al., 2012). It has been theorized that as the tibia goes through internal rotation, it creates greater stress on the lateral portion of the femoral surface (Lafortune, Cavanagh, Sommer, & Kalenak, 1994). When the tibial tuberosity inwardly rotates, the patellar tendon attachment forces the patella to rotate. This rotation of the patella about the frontal plane decreases the contact area of the patella on the femoral condyles, creating higher pressures in the joint (Lee, Morris, & Csintalan, 2003).

Manipulations of eversion characteristics have been seen to affect tibial rotation. In one study, subjects walked in three different shoes: a standard sole, one with a valgus wedge and one with a varus wedge in the sole. Researchers found that peak tibial internal rotation was decreased when subjects wore shoes with a varus wedge (greater inversion), and was greatest when wearing shoes with a valgus wedge (Lafortune et al., 1994). This indicates that when the foot's eversion ROM was increased with the valgus wedge, the tibia's internal rotation was also increased. While dorsiflexion was not looked at in this study, it may be expected that the varus wedge allowed the subject to go through a greater range of motion. Peak internal tibial rotation has been correlated with peak rearfoot eversion in subjects with PFPS by Barton et al. (2012), yet they did not examine dorsiflexion motion.

Dorsiflexion During a typical gait cycle after initial contact, the ankle pronates, and the tibia is forced to internally rotate on the talus while the foot everts and the ankle dorsiflexes. When a runner lands, their tibia is in an externally rotated position. During this initial foot strike is when the body needs to create mechanisms to absorb the impact of the body. While the foot pronates, the tibia is forced into internal rotation while the knee simultaneously flexes (Lafortune et al., 1994). If this flexion is coupled with too much internal rotation, there may be excessive stresses on the patellofemoral joint.

When the ankle goes through eversion either during gait or landing, it simultaneously dorsiflexes to allow the body to absorb the ground reaction forces. In a healthy athlete, these actions occur almost simultaneously. It has been theorized that it is not necessarily the amount of pronation that may be problematic, but more so its timing, yet there have been no differences seen in subjects with and without patellofemoral pain (Powers & Chen, 2002; Rodrigues, 2011). When the runner develops a faulty movement pattern, it may be due to any of the specific movements involved with pronation. If there is a lack of dorsiflexion mobility, the forces normally absorbed by this motion during the initial phases of gait need to be compensated for elsewhere. Theoretically, this compensation likely occurs with rearfoot eversion and consequently affects the kinetic chain with increases in internal tibial rotation and knee valgus (Tiberio, 1987). Limited dorsiflexion has been seen in patients with patellofemoral pain syndrome, and it is has been proposed that this limitation may be compensated for by excessive pronation (Levinger, Gilleard, & Coleman, 2007). One prospective study found subjects with PFPS to have less flexibility in both their quadriceps and gastrocnemius muscles (Witrouw et al., 2000). Another prospective study characterized both the gastrocnemius and soleus muscles to have less range of motion in patients who went on to suffer patellofemoral pain (Piva et al., 2009).

These findings suggest that without adequate dorsiflexion mobility, the body may need to compensate in other ways to allow for absorption of the forces of running. Thus determining how different individuals move based on their dorsiflexion ROM will give insight as to how the body may transfer kinematic differences at the ankle up the kinetic chain.

Role of Dorsiflexion Range of Motion in Landing

When landing from a jump or fall, the body must be able to stabilize and absorb all of the forces of impact. Improper or faulty biomechanics during a land may create undue stress on many of the structures of the lower extremity. Specifically, increased knee valgus during athletic-type movements is implicated as a risk factor for both acute (Hewett et al., 2005) and overuse injuries at the knee (Mizuno et al., 2001).

A study by Fong et al. (2011) examined the relationship between dorsiflexion range of motion and biomechanical variables during a jumping task. Their hypothesis was based upon the idea that those with greater DFROM would go through a "softer" landing. A "soft" landing is characterized by greater amounts of flexion in all joints of the lower extremity as well as lower peak vertical ground reaction forces than "stiff" landings (Devita & Skelly, 1992). The researchers found that those who had greater DFROM when measured with an extended knee also had greater knee-flexion displacement than those with lesser DFROM. Interestingly, when DFROM was measured with a bent knee, the same relationship was not significant (though a trend was seen). This was attributed to the fact that the gastrocnemius is the prime contributor to force attenuation during the landing task, and measurement with a flexed position at the knee measures primarily flexibility of the soleus (Fong et al., 2011).

Summary

In summary, risk factors for patellofemoral pain syndrome are extensive, but they are not fully understood. Distal risk factors have been emerging as an important area where the literature is inconclusive. Further, the role dorsiflexion range of motion plays in development of injury is unknown. Before implications for injury are determined, it is important to investigate how differing values of DFROM affect the knee.

Past studies have suggested decreased DFROM to be associated with increased knee valgus positioning (Macrum et al., 2012; Sigward, Ota, & Powers, 2008) as well as stiffer landings (Fong et al., 2011), but further analysis is needed to fully understand the biomechanics of those with differing ROM.

CHAPTER III

METHODS

Analysis of dorsiflexion ROM and knee biomechanics was done on previously collected data that was part of an 11-week resistance training study. Data used for analysis were collected at the conclusion of the intervention (i.e. during post test). This session was chosen because it allowed participants to be familiarized with all measurements taken.

Participants

Prior to recruitment, approval was gained from the University's Institutional Review Board. Participants were recruited from the female undergraduate population at the University of North Carolina at Greensboro. Participants were required to be recreationally active, but not be a member of any varsity level team. They were excluded if any neurological or vestibular diseases were present. Participants received compensation for their participation in the study. Before any data were collected, participants read and signed an informed consent. Nineteen participants took part in this study (20 ± 1.3 years, 1.61 ± .06 m, and 67 ± 10.7 kg).

Drop Jump

For each data collection session, three independent optical LED marker sets (Phase Space, San Leandro, CA) were applied to participants' left foot, leg, and thigh using hook and loop material attached to compression shorts and calf sleeves. Markers were also applied to the sacrum via adhesive spray and double-sided tape.

Participants were given standardized athletic shoes to wear during testing. Joint centers were determined by the centroid (ankle and knee) and rotational methods (hip). Participants were instructed to perform a drop jump from a 45 cm wooden box. They were instructed to stand at the edge of the box so the distal third of their feet were hanging off the edge, then to "fall" off the box onto a force plate. Upon landing, they were to immediately jump straight up into the air to maximum vertical height. Throughout testing, they were instructed to place their hands at ear level to reduce influence from the upper extremity and not to obscure the LED markers. Prior to data collection, the process was demonstrated, and each participant was allowed at least three practice trials to ensure they could correctly fall off the box. No special instructions or feedback on the biomechanics of the participants was given in order to ensure they were performing the landing as naturally as possible. Five trials were recorded and used for data collection, and participants were allowed a 1-minute break between trials. Trials were considered unacceptable if the participant either lost their balance, did not land completely on the force plates, or if they appeared to have jumped off the box rather than "falling."

Biomechanical data were processed using MotionMonitor Software (Innovative Sports Training, Chicago, IL USA) and custom MATLAB (MathWorks, Natick, MA USA) code. Kinetic data were collected at 1000 Hz and kinematic data were collected at 240 Hz and both were low-pass filtered at 12 Hz using a 4th order, zero lag Butterworth filter. Three dimensional kinematics were quantified using a segmental reference system. Joint motion about defined axes (in the pelvis, thigh, and shank) was described using Euler's equations, with a rotational sequence of Z (flexion/extension) Y' (internal/external rotation) X'' (abduction/adduction). Flexion, internal rotation, and adduction were measured as positive. Data were collected for 3 seconds: beginning at 0.5 seconds prior to ground contact (defined as >10N vGRF) and concluding 2.5 seconds following ground contact. Data at the hip, knee, and ankle were extracted from initial ground contact to peak knee flexion. The average values from five acceptable trials were used for analysis.

Knee angles were recorded and extracted for analysis in the frontal, transverse, and sagittal planes at: initial ground contact and peak knee flexion, and total excursion was calculated (peak-initial). The same process was repeated for sagittal plane angles at the ankle and hip. Inverse dynamics calculations were used to determine joint moments for the extensor muscles of the lower limb (knee extensor, hip extensor, ankle plantar flexors). Joint stiffness and joint energy absorption were also calculated (Schmitz & Shultz, 2010) for analysis.

Dorsiflexion Range of Motion

Each subject's weight-bearing dorsiflexion range of motion (DFROM) was measured barefoot on the left side following procedures described by Bennell et al. (1998). Prior to any measurements, a mark was made on the anterior tibia 10 cm distal to the tibial tuberosity. Participants were then instructed to perform a standing calf stretch 2 times for 30 seconds each. They were brought to a line drawn on the ground perpendicular to a vertical line made on the wall. They were instructed to align their second toe and heel of the right leg with the center of the line on the floor. Next, participants were instructed to lunge forward and touch their knee to the line on the wall while maintaining heel contact with the ground (Figure 4).

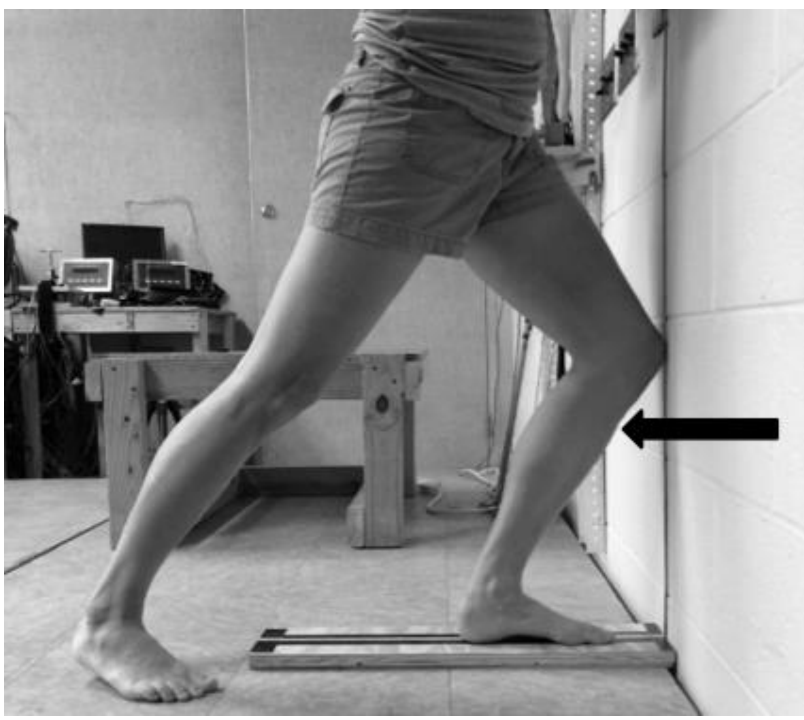

Figure 4. Position for Measurement of Dorsiflexion Range of Motion.
Arrow Indicates Location of Inclinometer.

The subject began 10 cm away from the wall, and moved away until they could no longer maintain heel contact with the floor. Then, they were instructed to move forward in 2 mm increments until they were able to touch the wall with their heel on the ground. An inclinometer zeroed at the wall was then placed on the previously made mark on the tibia and the DFROM angle was recorded to the nearest degree. This process was repeated three times, and an average of the three trials was calculated and used for analysis.

Data Analysis

DFROM values, kinematic, and kinetic data were entered into Microsoft Excel and SPSS v21.0 (IBM Corp, Armonk, NY) for analysis. Pearson product-moment correlations were calculated to determine the relationships between DFROM and ankle (sagittal) and knee (sagittal, frontal and transverse) initial and excursion values. Correlations between DFROM and ankle plantar flexion moment, knee extensor moment, and hip extensor moment were also calculated to determine the effects DFROM had on kinetics. In addition, correlations between DFROM and stiffness and work absorption were calculated to further understand the energetics of the task. An alpha level of $P < .05$ was used for all analyses.

CHAPTER IV

RESULTS

Values for participant's DFROM were between 38.7-68.7° (Mean = 47.3°, Standard Deviation = 7.1°, Figure 5). Descriptive information and relationships between all variables and DFROM are seen in Table 1. As expected, initial values at landing were not related to dorsiflexion range of motion. However, in the sagittal plane, greater DFROM was associated with greater peak ankle dorsiflexion and knee flexion (Ankle: r = .637, p = .003, Figure 6; Knee: r = .604, p =.006, Figure 7), and greater total knee flexion and hip flexion excursion (Knee: r = .634, p=.004, Figure 8; Hip: r = .461, p = .047, Figure 9). No other kinematic relationships were significant.

Table 1. Descriptive Statistics and Relationships between Kinematic Variables and Dorsiflexion Range of Motion (DFROM).

Variable		Range (degrees)	Mean ± SD (degrees)	Pearson's r	p value
Ankle Dorsiflexion	Initial	35.8 – 70.4	44.8 ± 8.2	0.070	0.776
	Peak	95.8 – 112.3	104.5 ± 4.9	0.637*	0.003
	Excursion	31.9 – 69.3	59.7 ± 8.3	0.309	0.198
Knee Flexion	Initial	-8.4 – 22.4	4.1 ± 8.4	0.208	0.392
	Peak	63.9 – 119.8	80.1 ± 13.8	0.604*	0.006
	Excursion	57.0 - 97.4	76.0 ± 10.4	0.634*	0.004
Knee Rotation	Initial (IR)	-16.1 – 8.2	-1.5 ± 7.5	0.124	0.612
	Peak	-6.7 – 22.7	13.0 ± 6.8	0.147	0.548
	Excursion	5.1 – 28.3	14.5 ± 6.3	0.009	0.971
Knee Valgus	Initial	-5.2 – 7.01	1.2 ± 4.0	0.119	0.628

	Peak	-15.3 – 2.6	-6.7 ± 5.4	.253	.296
	Excursion	-16.7 - -1.6	-7.9 ± 4.9	.183	.452
Hip Flexion	Initial	-6.4 – 36.0	14.4 ± 11.7	-.183	.453
	Peak	37.1 – 85.7	63.3 ± 12.7	.379	.109
	Excursion	13.3 – 77.6	49.0 ± 15.1	.461*	.047
Hip Rotation	Initial	-12.2 – 4.0	-3.3 ± 3.4	.003	.991
	Peak	-2.7 – 14.0	4.5 ± 4.9	.281	.243
	Excursion	0.2 – 14.9	7.8 ± 4.3	.318	.184

* p < .05

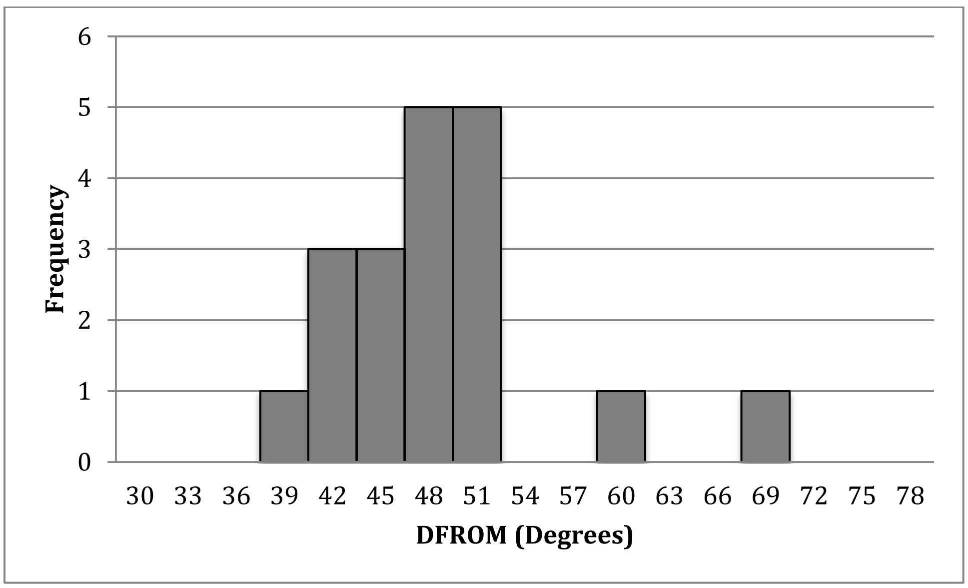

Figure 5. Histogram of DFROM Values.

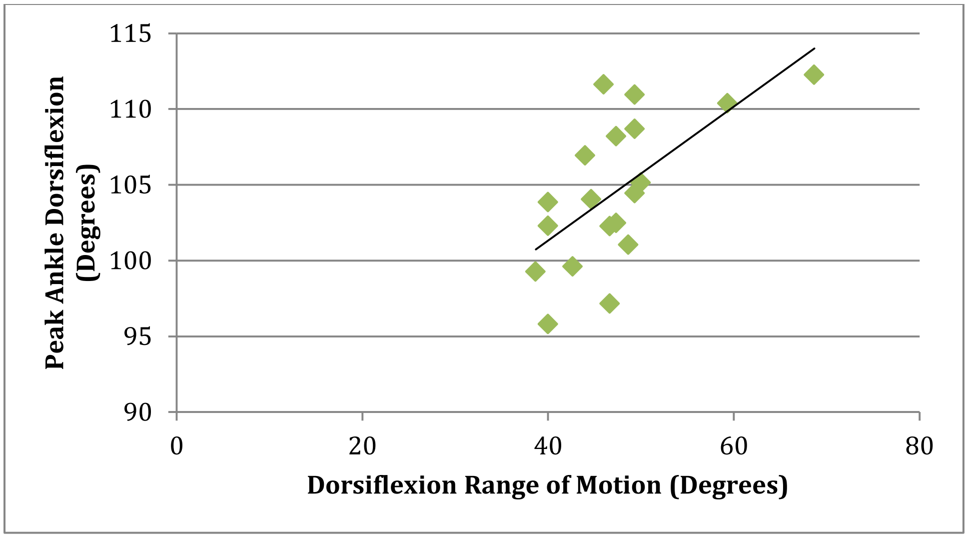

Figure 6. Relationship Between DFROM and Peak Ankle Dorsiflexion During Drop Jump Landing.

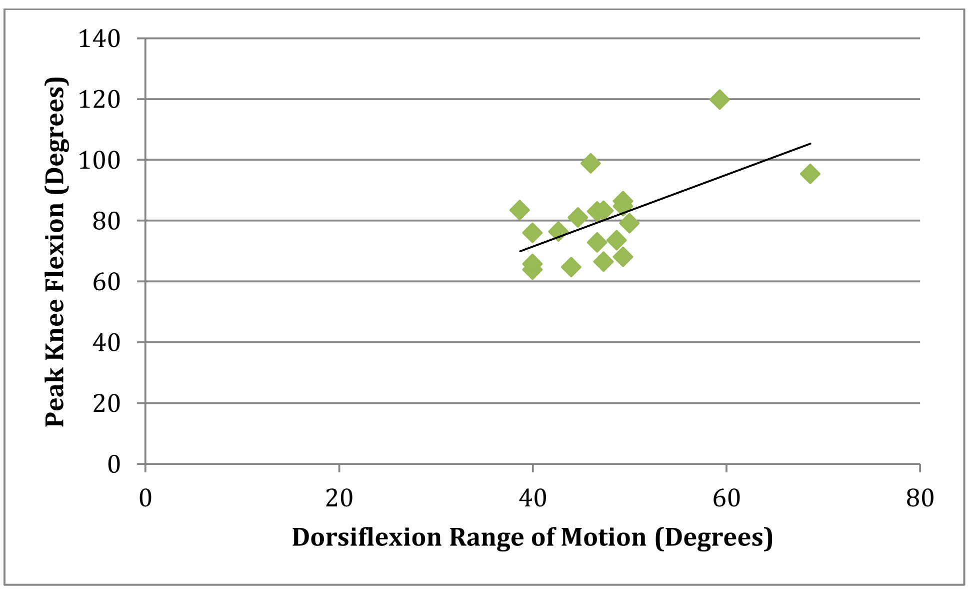

Figure 7. Relationship Between DFROM and Peak Knee Flexion During Drop Jump Landing.

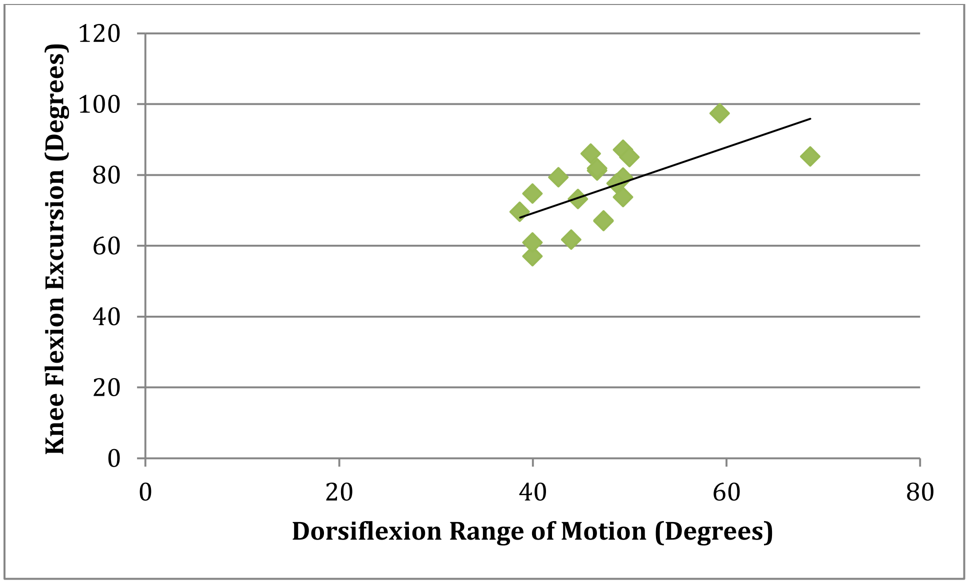

Figure 8. Relationship Between DFROM and Knee Flexion Excursion During Drop Jump Landing.

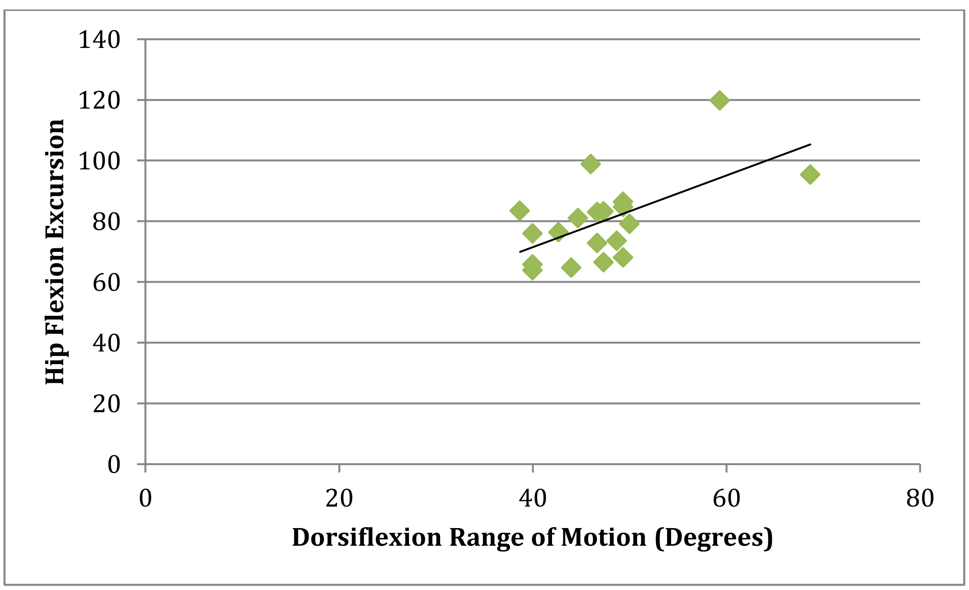

Figure 9. Relationship Between DFROM and Hip Flexion Excursion During Drop Jump Landing.

Significant relationships were also observed between DFROM and knee and hip sagittal plane work absorption (Knee: $r = -.456$, $p = .049$, Figure 10; Hip: $r = -.524$, $p = .021$, Figure 11, Table 2). No other kinetic relationships were significant (Table 2).

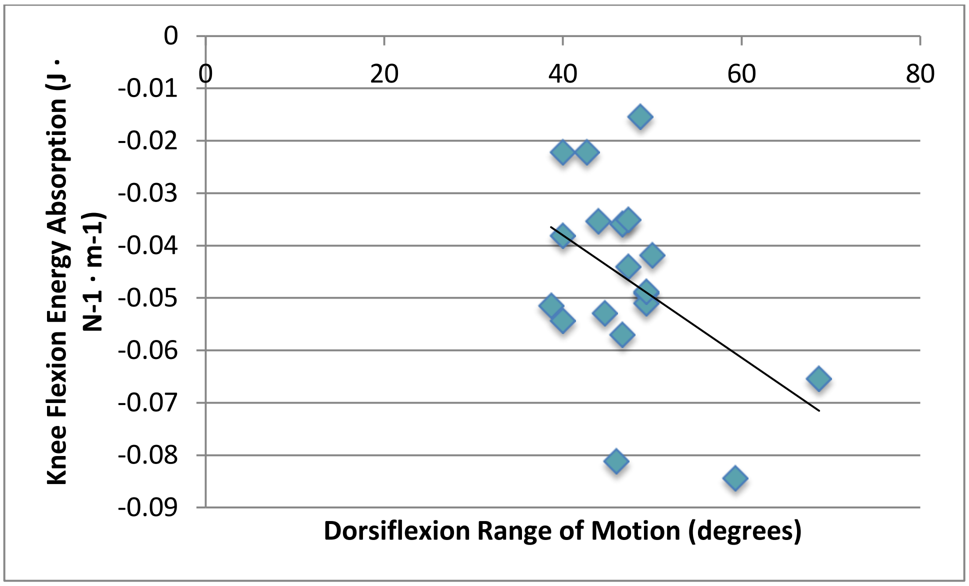

Figure 10. Relationship Between DFROM and Knee Flexion Energy Absorption During Drop Jump Landing.

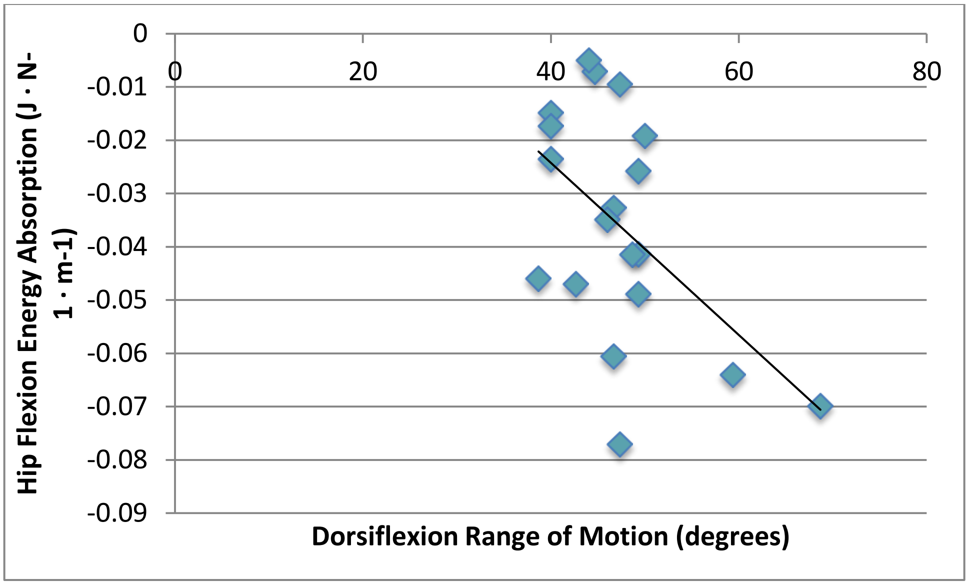

Figure 11. Relationship Between DFROM and Hip Flexion Energy Absorption During Drop Jump Landing.

Table 2. Descriptive Statistics and Relationships between Kinetic Variables and Dorsiflexion Range of Motion (DFROM).

Independent Variable	Range	Mean ± SD	Pearson's r	p value
Peak Flexion Moment ($Nm \cdot N^{-1} \cdot m^{-1}$)				
Ankle	-0.122 - -0.062	-0.047 ± 0.017	-.389	.099
Knee	-0.104 - -0.040	-0.072 ± 0.018	-.287	.233
Hip	-0.155 - -0.038	-0.099 ± 0.029	-.087	.724
Sagittal Plane Stiffness ($Nm \cdot N^{-1} \cdot m^{-1} \cdot degrees^{-1}$)				
Ankle	-0.00310 - -0.00062	-0.00126 ± 0.00056	.005	.985
Knee	-0.00174 - -0.00051	-0.00096 ± 0.00026	.103	.676
Hip	-0.00474 - -0.00096	-0.00220 ± 0.00091	.241	.320
Flexion Energy Absorption ($J \cdot N^{-1} \cdot m^{-1}$)				
Ankle	-0.088 - -0.023	-0.055 ± 0.015	-.404	.086
Knee	-0.084 - -0.015	-0.047 ± 0.018	-.456*	.049
Hip	-0.077 - -0.005	-0.036 ± 0.022	-.524*	.021

* $p < .05$

CHAPTER V

DISCUSSION

The primary findings of this study were that greater ankle dorsiflexion range of motion (DFROM) was associated with greater peak ankle dorsiflexion and knee flexion, greater knee and hip flexion excursion, and greater knee and hip work absorption. Thus, our hypotheses were partially supported. While less DFROM affected sagittal plane biomechanics, this did not result in compensatory increases in transverse and frontal plane knee motion.

Contrary to our hypothesis, reduced dorsiflexion was not associated with greater frontal plane motion. Results of previous studies which showed greater medial knee displacement with restricted dorsiflexion (Bell et al., 2008; Hagins, Pappas, Kremenic, Orishimo, & Rundle, 2007; Macrum et al., 2012; Sigward et al., 2008) caused us to speculate that restricted DFROM upon landing would result in compensatory subtalar pronation, and subsequently greater tibial rotation and knee valgus further up the chain. Our results agree with some (Fong et al., 2011), but not others (Bell et al., 2008; Hagins et al., 2007; Macrum et al., 2012; Sigward et al., 2008). This may in part be due to the different methods by which prior studies have measured DFROM, and that much of the previous work has examined restrictions in DFROM through mechanical means (e.g. mechanical blocks).

Sigward et al. (2008) examined frontal plane knee excursion in young (mean = 15.5 years) female soccer players during a drop jump task, and reported greater frontal plane excursion in those with less DFROM when dorsiflexion was measured passively with the knee flexed to 30°. However, they determined DFROM accounted for only 10.8% of the variance in frontal plane knee excursion. Similarly, Bell et al (2008), examined medial knee displacement (frontal plane excursion) during an overhead squat, separating participants into groups based on if they did or did not exhibit medial knee displacement during the squatting task. While there was no significant difference in DFROM in those who did and did not display medial knee displacement, they noted a trend toward significance ($p = .06$) when DFROM was passively measured with the knee flexed to 30°, but not when measured with the knee extended ($p = .23$). Additionally, while Fong et al. (2011) observed no relationships between DFROM and frontal plane excursion during a drop jump task when DFROM was measured non-weight bearing with the knee in both flexed and extended positions, they also observed a trend toward more frontal plane excursion in those with less dorsiflexion (Flexed: $p = .053$, Extended: $p = .091$).

In each of these cases, DFROM was measured passively by an examiner in non-weight bearing, which may be inherently different than the range that might be measured in weight bearing (Rabin & Kozol, 2012). When DFROM is measured in weight bearing, the joint moment is three to four times greater (Rabin & Kozol, 2012) than when non-weight bearing, which may better reflect the available joint motion that occurs during more dynamic weight bearing movements. In support of this premise, the DFROM values we obtained in weight bearing were 44.8 ± 8.2 as compared to -3.5 ± 3.5 – 18.9 ± 5.9 as measured by prior studies in non-weight bearing (Fong et al., 2011; Sigward et al., 2008). In addition, measuring DFROM in weight bearing vs. non-weight bearing may affect the extent to which subtalar motion or eversion contributes to the measure. In full weight bearing, it is likely that any movement toward pronation or eversion is already taken up, thus the measurement largely isolates ankle dorsiflexion. However, in non-weight bearing, unless efforts were made to maintain the subtalar joint in neutral, the measure may have reflected a combination of dorsiflexion and pronation or eversion. Because ankle kinematics were not measured while deriving these measures of DFROM in weight bearing and non-weight bearing, it is difficult to draw definite conclusions, but it may be that the amount of available pronation and eversion that is picked up in the measure is a stronger predictor of knee valgus than dorsiflexion range of motion alone, and may in part explain the differences in study findings. Future studies should examine the tri-planar motions at the ankle that occur with these weight bearing and non-weight bearing measure, and determine which component is most associated with frontal plane knee motion.

Other studies demonstrating a relationship between DFROM and knee valgus induced a dorsiflexion restriction through mechanical means. Both Macrum et al (2012) and Bell et al (2008) found that manipulating initial dorsiflexion angles altered peak knee valgus angles. Macrum et al (2012) used a wedge to simulate restricted DFROM, and observed significantly higher peak valgus angles in the wedge condition, but no difference in frontal plane joint excursion ($p = .15$). Bell et al (2008) observed a reduction in medial knee displacement when a block was used as a heel lift to put the participant in greater initial plantar flexion. Conversely, the present study examined natural physiological DFROM, which is likely more forgiving or “compliant” than a rigid mechanical block. Using a rigid block to limit dorsiflexion may have a created a situation where ankle eversion had to occur to complete the motion, which may have resulted in greater knee valgus motion. Collectively, these findings suggest that normal physiological ranges of dorsiflexion in weight bearing are not associated with greater frontal or transverse plane knee motion. However, we examined only healthy individuals, and did not measure pronation in this study. Because we studied only healthy individuals, it is possible that all subjects had sufficient dorsiflexion range of motion. If DFROM was sufficient, concomitant pronation may not have occurred to the extent needed for increases in knee valgus. That is, those who have pathological DFROM restrictions may have a greater need to evert during landing than a healthy population. However, because the current study did not measure subtalar pronation or eversion during the landing, it is difficult to determine the extent to which this did or did not occur. Therefore, it may be important to repeat this study in an injured population, both to determine if DFROM differs in this population, and if more extreme limitations in DFROM may contribute to increased subtalar pronation, thus frontal plane knee motion.

The finding that sagittal plane flexion values were lower in those with lower DFROM agree with previous findings by Fong et al (2011), who reported a significant positive relationship between extended-knee DFROM and knee flexion displacement ($r = 0.464$). The relationship trended toward being positive but did not reach significance when DFROM was measured with a flexed knee ($r = 0.327$, $p = 0.055$). In the current study, DFROM accounted for approximately 40% of the variance in knee sagittal plane excursion. This decrease in sagittal plane flexion motions may have implications for both overuse and acute injuries. Previous studies have indicated that less sagittal excursion may contribute to a "stiff" landing which in turn may increase vertical and posterior ground reaction forces and place greater stress on soft tissues structures, including the ACL (Devita & Skelly, 1992). ACL injuries are reported to commonly occur with the knee close to full extension (Hewett, Myer, & Ford, 2006), where the hamstring muscles are at a mechanical disadvantage to stabilize the tibia and reduce anterior tibial translation (Pandy & Shelburne, 1997).

Based on these assumptions, we examined whether less DFROM was also associated with greater joint moment, greater joint stiffness and greater work absorption. While we observed no relationship between less DFROM and greater joint moments or stiffness, we did observe strong correlations between greater DFROM with greater hip and knee energy absorption, likely driven by the greater joint excursions observed at these joints. Work absorption indicates the amount of eccentric work done during the landing phase of the drop jump (McNitt-Gray, 1993). Increased energy absorption has been suggested to be an important factor in reducing the shock of impact when landing from a jump or fall. The data from this study suggests that while reduced DFROM may not lead to detrimental forces at the knee, greater DFROM may have a protective effect by better mitigating the impact forces upon landing through contractile mechanisms.

From this perspective, results from this study suggest that preventative treatments to increase ankle dorsiflexion range of motion may be beneficial.

In summary, reduced dorsiflexion range of motion was associated with reduced sagittal plane knee motion and work absorption, which may reduce an athlete's potential to absorb the forces of landing. The impact this could have over time requires further study. In addition, reduced dorsiflexion range of motion had no impact on frontal or transverse plane hip and knee biomechanics, suggesting that factors other than dorsiflexion (e.g. pronation) may be impacting frontal plane knee motion.

This study was limited to healthy college-aged females with normal physiological DFROM during the first landing of a drop-jump task. The study did not measure potential compensatory motions of foot pronation in the frontal and transverse planes that could potentially have significant links with knee frontal plane motion. Further, results are limited to a laboratory setting, where participants were able to completely focus on the task without distraction.

Future studies should attempt on studying the effect of DFROM on a more varied population. While females are more likely to sustain both PFPS and ACL ruptures, males are not excluded from risk. Future work should measure DFROM both weight bearing and non-weight bearing in order to further investigate how these relationships may differ with knee function in weight bearing. Future work should also examine the kinematics of the ankle joint in the frontal and transverse planes to determine if any compensatory motions are occurring. Studies also may benefit from examining persons who currently are experiencing symptoms of overuse injuries to see if DFROM differs in these populations, and whether increasing DFROM may have any sort of protective impact on knee joint biomechanics.

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