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The Effects of Gait Retraining in Runners With Patellofemoral Pain

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THE EFFECTS OF GAIT RETRAINING IN RUNNERS WITH PATELLOFEMORAL PAIN

BY

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The Effects of Gait Retraining in Runners With Patellofemoral Pain

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ABSTRACT

Running popularity has increased resulting in a concomitant increase in running-related injuries. Of these injuries, patellofemoral pain (PFP) is the most commonly reported. **PURPOSE:** The purpose of this study is to determine whether gait retraining by modifying footstrike patterns from rearfoot strike (RFS) to forefoot strike (FFS) reduces PFP and improves associated biomechanical measures, and whether the modification results in increased risk of ankle injuries. **METHODS:** Sixteen subjects (n=16) received clearance to participate by a licensed physical therapist, and were randomly placed in the control (n=8) or experimental (n=8) group. Subsequently, the experimental group (EXP) performed eight gait retraining running sessions where footstrike pattern was switched from RFS to FFS, while the control group (CTL) performed eight running sessions with no intervention. Knee flexion (Kflex), knee valgus (Kvalg), and ankle flexion (Aflex) at initial contact, knee (KL) and ankle loading (AL), patellofemoral contact force (PFCF), patellofemoral stress (PFS), Achilles' tendon force (ATF), and knee pain as reported on a visual analog scale (VAS) were recorded pre-, post-, and one-month post-running trials.

RESULTS: In Exp, knee pain was significantly reduced post-retraining (mean Δ, -4.225; $p<0.05$) and at one-month follow-up (mean Δ, -4.276; $p<0.05$). Kflex was significantly increased post-retraining (mean Δ, 6.044°; $p<0.05$). Kvalg was significantly improved post-retraining (mean Δ, 2.782°; $p<0.05$) at one-month follow-up (mean Δ, 4.066°; $p<0.05$). Aflex was significantly different post-retraining (mean Δ, -23.958°; $p<0.05$), as well as AL post-retraining (mean Δ, 14.738°; $p<0.05$) and one-month follow-up (mean Δ, 17.192°; $p<0.05$). PFCF, PFS, ATF, and KL were not significantly different.

CONCLUSION: Retraining from RFS to FFS results in significant reductions in knee pain in runners with PFP without increasing risk of ankle injuries.

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SYMBOLS/ABBREVIATIONS

≥: greater than or equal to

>: greater than

≤: less than or equal to

<: less than

±: plus or minus

~: approximately

%: percent

ACL: anterior cruciate ligament

Aflex: ankle flexion at initial contact

AL: ankle loading

ANOVA: Analysis of variance

ATF: Achilles' tendon force

Bpm: beats per minute

BW: Body weight

CI: confidence interval

cm: centimeters

COP: center of pressure

CoT: cost of transport

CTL: control group

EXP: experimental group

FFS: forefoot strike

Fq: quadriceps force

FSA: foot strike angle

HR: heart rate

k: constant

Kflex: knee flexion at initial contact

kg: kilograms

KL: knee loading

La: Achilles' lever arm

Kvalg: knee valgus at initial contact

Lq: moment arm of the quadriceps mucles

LR: loading rate

Ma: plantarflexion moment

MFS: midfoot strike

Mk: knee extensor moment

MPa: megapascal

n: number of subjects

N*m/kg: Newton-meters per kilogram

PFCF: patellofemoral contact force

PFP: patellofemoral pain

PFS: patellofemoral stress

POST: post test

PRE: pre test

RFS: rearfoot strike

ROM: range of motion

SD: Standard deviation

SI: strike index

THM: time between the heel and metatarsal acceleration peaks

VAS: visual analog scale

vGRF: vertical ground reaction force

VO_2: oxygen consumption

x: knee flexion angle

yrs: years

CHAPTER 1

Introduction

Recreational running is one of the most popular modes of regular exercise. However, the repetitive stress on the body due to running can cause chronic injuries. It has been estimated that approximately 36 million people run regularly as part of their exercise program. Of those people, it has been reported that somewhere between 20-80% of recreational runners get injured at least once a year (1), and somewhere between 20-70% of those injured will get reinjured in the same year. The most common running injury sustained is patellofemoral pain (PFP) at the knee (2). PFP is defined as knee pain originating from contact of the posterior surface of the patella and the femur, however, the etiology is still unclear (3). However, overuse, muscular imbalance of the lower extremity, and patellofemoral malalignment have been noted as common factors increasing the risk of PFP (3). Our study will focus on overuse in runners who run at least 10 miles per week, and we will employ strategies of gait retraining to determine if changing footstrike patterns from a rearfoot strike (RFS) to a forefoot strike (FFS) will decrease the incidence and/or severity of PFP.

Footstrike patterns vary between and among runners and range from RFS to midfoot strike (MFS) to FFS, with each pattern producing different kinetics and kinematics which can cause different structural perturbations. Typically, RFS is defined as initial contact at the posterior 1/3 of the foot. MFS contacts the central 1/3 of the foot first and FFS is defined as initial contact at the anterior 1/3 of the foot. Footstrike patterns are developed early in life with very few changes being made as an individual ages, however, it has been demonstrated that runners will change their footstrike pattern to more of a RFS throughout the course of a marathon (4) which may be due to the lower running economy seen with RFS (5).

In a recent pilot study done in our laboratory (data unpublished), we were able to determine that rearfoot striking while running was associated with increased knee valgus compared to forefoot striking. Others have determined that forefoot striking decreased patellofemoral contact force and patellofemoral stress (6). Therefore, it is possible that the use of a forefoot strike decreases PFP by minimizing patellofemoral stress, which may be associated with overuse. It is probable that gait retraining using foot strike patterns as the focus may decrease PFP in runners with chronic symptoms. This is the focus of our investigation.

Forefoot Strike vs. Rearfoot Strike

Despite gait pattern being a significant factor for exercise-related lower-leg pain (7), approximately 75% of shod runners continue to heel strike (8), possibly due to increased perceived comfort (9). Rear foot cushioning is thicker than the forefoot cushioning on running shoes and possibly makes RFS more stable compared to FFS (10). Additionally, when running with a FFS, there is a different movement pattern of the center of pressure, which allows for the loading of the arch to turn the ground reaction force energy into rotational energy (distributes a vertical force into mediolateral force). It also activates inactive musculature in the foot (11-12), and increases loading at the ankle joint (13-14) and Achilles tendon (15). The increased loading at the ankle joint and in the Achilles tendon may cause discomfort among runners who switch to a FFS, however limited research exists to support this notion. Additionally, forefoot striking reduced the patellofemoral moment (6), suggesting that it may also decrease running-induced knee injuries, specifically PFP. However, because this is a relatively new hypothesis, limited research exists supporting it, with newer research presently emerging.

Decreased dorsiflexion of the foot is also seen when forefoot striking (6). Decreased dorsiflexion at initial contact leads to an increase in knee flexion at touch down, which was demonstrated while barefoot running with a forefoot strike when compared to shod running with a rearfoot strike (16). It is noteworthy that increased knee flexion at touch down is associated with increased hamstrings and decreased quadriceps activation (17). Potentially this may distribute the force (ground reaction force) among the contractile properties of the leg (muscles) and help prevent excessive force absorption among the non-contractile properties of the leg (ligaments), which may reduce running-related knee injuries.

Gait Retraining

The concept of gait retraining through footstrike pattern manipulation challenges the current research, which focuses on gluteal activation (18-20). The concept of gluteal retraining stems from the notion that PFP may be due to increased Q angle (quadriceps angle- drawn from the anterior superior iliac spine to central patella and a second line drawn from the central patella to tibial tubercle), however evidence has been inconsistent as to whether this idea is valid (21). In a recent review, it was suggested that increased knee valgus may have a significant impact on PFP and ACL injuries (22). It has been reported that knee valgus increases the strain on the ligaments in the knee (23-24). Therefore, the proposed study will add to our understanding of the relationship between PFP and footstrike pattern during running, and partially fill the void in the literature to determine if footstrike manipulation is an appropriate recommendation to make for runners with chronic knee pain.

Study Purpose and hypotheses

The purpose of the study is to determine whether gait retraining from a rearfoot strike to a forefoot strike changes selected running kinetics and kinematics at the knee in habitual heel striking recreational runners with chronic knee pain, specifically PFP. We will also determine if there is a reduction in their pain symptoms one-month post-retraining. The proposed mechanism of knee pain reduction is through the decreased patellofemoral stress and contact force associated with forefoot striking resulting in a reduction of force applied to the patellofemoral region of the knee thus. Additionally, we will observe any changes in ankle kinetics/kinematics.

Purposes of the study

1. To demonstrate whether RFS is associated with increased patellofemoral stress/contact force, knee valgus at initial contact, and knee pain and pain occurrence with decreased knee flexion, ankle plantarflexion, Achilles tendon force, and oxygen consumption.
2. To assess whether gait retraining leads to decreased patellofemoral stress/contact force, knee valgus at initial contact, and knee pain and pain occurrence in runners with running-related chronic knee pain, while increasing knee flexion, ankle plantarflexion, Achilles tendon force, and oxygen consumption.
3. To demonstrate whether changes associated with retraining are maintained one-month post-retraining sessions and assess whether oxygen consumption returns to pre-retraining values.

Hypotheses

Our study will be testing the following hypotheses:

1. Immediately post gait retraining, subjects will decrease patellofemoral stress and patellofemoral contact force.

   Previous research has shown that patellofemoral stress and patellofemoral contact force decrease with an acute bout of running with a forefoot strike (6). However, it has not been shown that these decreases are maintained after two weeks of gait retaining.

2. Subjects will maintain reductions in patellofemoral stress and patellofemoral contact force one-month after gait retraining.

   It was demonstrated that subjects decrease these variables acutely (6). However, it has not been shown that subjects will maintain these changes after resuming their normal running program outside of the laboratory for one month.

3. One-month post gait retraining, runners with chronic, running-related knee pain will report a significant decrease in pain severity.

   It has been demonstrated that with gait retraining using gluteal activation, subjects decreased pain severity (18-20), but it has not been demonstrated that gait retraining using a change in footstrike pattern will also decrease knee pain while running. A reduction in patellofemoral stress/contact force should reduce knee pain severity (6).

4. One-month post gait retraining, runners with chronic, running related knee pain will report a significant decrease in the occurrence of their symptoms.

It was demonstrated that gait retraining using glute activation decreased occurrence of knee pain in runners (18), however it has not been shown that gait retraining with a change in footstrike pattern will do the same. A reduction in patellofemoral stress/contact force (6) and subsequent severity in knee pain should reduce the occurrence of knee pain while running.

5. After gait retraining, subjects will show decreased knee valgus and knee loading, and a significant increase in knee flexion angles at initial contact.
   It has been demonstrated after acute bouts of forefoot striking that subjects decrease the knee valgus and increase knee flexion angles at initial contact (25), but it has not been shown that subjects maintain these changes after gait retraining. Retraining with a forefoot strike should allow runners to maintain these changes as it becomes more natural to them.
6. After gait retraining, subjects will significantly increase ankle plantarflexion, ankle loading, and Achilles tendon force without an increase in reported ankle pain.
   It has been demonstrated that there is increased ankle loading with a forefoot strike (13), but it has not been shown that gait retraining with a change in footstrike pattern will increase ankle plantarflexion (and loading) and cause ankle injury and/or pain.
7. One-month after gait retraining, oxygen consumption will not be significantly different compared to pre-retraining values.
   It has previously been demonstrated that after an acute change from RFS to FFS, oxygen consumption increases (5), but it has not been demonstrated whether these

values return to pre-retraining values after one month of using the modified gait pattern. After using the modified gait pattern for one month, subjects should make technical improvements in their movement through neural adaptations, leading to a reduced metabolic cost of the gait pattern.

Scope of the study

An *a priori* power analysis with an $\alpha = 0.05$ and an effect size of 0.25 to produce a power of 0.8 ($1 - \beta$) determined that 16 adult male and female runners will be needed for the current study. The subjects must run at least 10 miles per week, self-identify as a habitual heel-striker when running and have had the presence of PFP or some other chronic, running-related knee pain within the past three months. Subjects will fill out questionnaires about their pain levels and will be included in the study if they indicate that their pain level is at least "3" on a "0" to "10" pain scale with "0" indicating the absence of pain and "10" meaning the worst pain possible. Selection criteria will include heel strikers with no current lower extremity injury other than the presence of PFP or some other chronic, running-related knee pain, and currently running as a part of their regular exercise regimen. Subjects chosen for the experimental group will be included only if they agree to abstain from any additional running outside of the study during the retraining phase of the study.

Eight subjects (experimental group) will perform eight gait retraining sessions in the laboratory during a two week period, and the control group (n=8) will continue their normal running routine. The subjects will be randomly sampled into either the control or experimental group. Randomization will be done within sex to ensure equal representation and reduce the likelihood of influence of sex-specific variables. Pre- and post- retraining running sessions will be conducted to measure selected kinetic and kinematic variables, and the same testing will be done at equal time intervals for the control group.

Subjects will undergo a physical assessment by a physical therapist to confirm the presence of PFP (or other running-related, chronic knee pain) and video assessment will be done to confirm presence of a rearfoot strike while running. Potential participants will not be eligible to be in the study if they do not meet these two criteria. For the purpose of this study, rearfoot strike will be defined as a foot strike angle more than 8 degrees at initial contact, which is similar to previous research (6).

After confirmation of PFP and heel-striking, eligible subjects will perform a running trial to measure knee valgus, knee flexion and loading, ankle flexion and loading, patellofemoral stress (6), Achilles tendon force (26), patellofemoral contact force (27), and oxygen consumption (VO2). Pace will be controlled using a metronome set for their self-selected running speed at a speed chosen for a 30 minute run. Subjects will be given a new pair of neutral running shoes to use for the duration of the study. No orthotic devices will be allowed. This will be done to potentially minimize gait perturbations associated with different types of shoes and wear patterns that occur over time due to the footstrike pattern used prior to retraining.

Following completion of the pre-training running trial, subjects in the experimental group will perform eight gait retraining sessions to take place over two weeks as previously described by Noehren et al. (18). The control group will not receive the gait retraining intervention and continue their normal running regimen. For the retraining sessions, run time will gradually increase from 10 to 30 minutes. Mirror feedback and scripted statements, such as "run on your toes" and/or "run on the balls of your feet" will be used. Although mirror feedback is not as accurate as real-time feedback using motion analysis systems, it is a field method that can be used by individuals outside of the research setting. If necessary, subjects will receive additional feedback. During the first four sessions we will give subjects continuous feedback. During the last four sessions, the feedback will be gradually removed (18). At the end of each training session, subjects will report effort of execution and naturalness of the foot strike pattern on a scale of "1" to "10" with "1" being very hard to execute/unnatural and "10" being easy execution/natural (28). Once the retraining phase has been completed, the subjects will perform a post re-training running trial at the same running speed as the first running trial. The control group will perform this same post-testing approximately two weeks after their first test. Following the post-test, the subjects in the experimental group will be permitted to return to their normal running regimen. Running trials will be performed again at 1-month post re-training to compare changes in selected kinetic and kinematic variables and see if any pain/injuries appear after use of the new footstrike pattern for the experimental group. The control group will also perform another running trial one month after their second running trial.

A mixed model ANOVA (group x time) will be used to measure the mean differences between the groups for the variables of interest (knee valgus and flexion angle at initial contact, knee loading, ankle flexion at initial contact, ankle loading, patellofemoral stress, patellofemoral contact force, and Achilles tendon force). Comparisons will be made between the control and experimental group, and between

PRE- training, POST- training and 1-month after study completion for each group. Significance will be set at $\alpha<0.05$.

Limitations

This study will only follow subjects for one-month post retraining and, therefore, will be unable to demonstrate that the retraining changes are maintained in the long term. Because this is one of the first studies using gait retraining with a footstrike pattern change, we do not know the long term consequences associated with changing footstrike patterns. Subjects will be instructed to suspend any running outside of the laboratory during the retraining phase and the results could be affected if the subjects do not follow this instruction or if they skip multiple retraining sessions. Finally, it is unknown if the new footstrike pattern post retraining will increase the risk of sustaining other injuries, specifically at the ankle due to the increased ankle loading demonstrated in previous studies.

Significance

If the hypotheses are confirmed, the concept of gait retraining to a forefoot strike could help many runners alleviate and/or prevent reoccurrence of chronic knee injuries, specifically PFP. Additionally, this concept could help athletic trainers and other sports medicine professionals implement preventative training strategies that could potentially decrease knee injuries in athletic populations as well. Currently, there are limited strategies that prevent running-related chronic knee injuries, with focused/increased glute activation being one method recently studied (18-20).

Definitions

Patellofemoral pain (PFP) – pain or discomfort that occurs during or after physical activity originating from contact of the posterior of the patella with the femur

Patellar malalignment – translational or rotation deviation of the patella relative to any axis

Gait retraining- acquiring a different running style by inducing chronic changes in running form

Knee valgus- inward (medial) collapse of the knee

Patellofemoral contact force (PFCF)- patellofemoral joint reaction force quantified using quadriceps force and a constant estimated from a given knee joint angle position

Patellofemoral stress (PFS) – amount of PFCF for a given patellofemoral contact area

Achilles tendon force (ATF) – amount of force exerted on the Achilles tendon for a given ankle angle

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CHAPTER 2

This chapter presents a review article, entitled "The Effects of Gait Retraining in Runners With Patellofemoral Pain" which has been accepted for publication by *The International Journal of Sports Sciences*. It is authored by Jenevieve Roper, Janet Dufek, and Christine Mermier. The manuscript follows the formatting guidelines of the journal.

The Effects of Gait Retraining In Runners With Patellofemoral Pain: A brief review

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Keywords injury, knee, lower extremity, running

ABSTRACT

Running popularity has increased significantly since the 1990's due to the well-known health benefits. While the number of participants has increased, there has also been a concomitant increase in running-related injuries. One of the most common running-related injuries is patellofemoral pain syndrome. Although the cause appears to be multifactorial, several different strategies have been researched and implemented as treatment. Gait retraining is relatively new and research has shown it reduces pain and improves function in runners affected by patellofemoral pain. Due to the many suggested biomechanical benefits associated with a forefoot strike pattern, it is possible to change foot strike patterns through a gait-retraining program and reduce pain and improve function in affected runners. Because of the increased load at the ankle during forefoot striking, future research should address whether changing foot strike patterns negatively affects ankle function.

Introduction

Running popularity has increased dramatically since the 1990's (Lynch, 2008). More than 15 million people participated in running events in 2012 compared to 4.6 million participants in the 1990's (Runningusa.org). Much of this increase has been due to the numerous reports about the health benefits associated with cardiovascular exercise (Dangardt, 2013; Dhaliwal, 2013; Kravitz, 2007). However, as the number of participants increase, so does the incidence of running-related injuries.

It has been reported that 19.4% to 79.3% of runners sustain running-related injuries (Newman, 2013; van Gent, 2007), with recreational and novice runners showing a higher incidence compared to competitive endurance runners (Buist, 2010; Tonoli, 2010). There are many risk factors associated with running with the most common risk factors are reported to be age, running experience, and injury history (Newman, 2013; Buist, 2010; Tonoli, 2010; Van Middelkoop, 2008; van Gent, 2007; Taunton, 2002). One of the most commonly reported injuries is patellofemoral pain and it has a high incidence among runners (van Gent, 2007; Taunton, 2002). Because the cause of patellofemoral pain is largely unknown (Thomee, 1999), it is difficult for clinicians to provide preventative strategies to runners that will help decrease the incidence and severity of this condition. This review will briefly examine patellofemoral pain and introduce a strategy that runners may employ to decrease their risk of developing this condition and other running related injuries.

Gait Cycle

Running has a distinct gait cycle, which is different than that of walking. Commonly, running is described as having two phases called stance and swing phase.

These have been further separated into four phases: stance phase, early float, swing phase, and late float (Lohman, 2011). Stance phase begins with foot contact and ends with toe off. One complete cycle begins at initial contact of one foot and ends with contact of the same foot; therefore, as running speed increases, the gait cycle occurs faster.

When analyzing running, stance phase is of particular interest as this is the phase where most injuries are thought to occur. Stance phase can be broken down further into initial contact, loading response, midstance, and terminal stance/preswing (Lohman, 2011). Initial contact is when the heel or toe initially hits the ground. A loading response occurs as the muscles of the thigh and leg contract (Novacheck, 1998) and the knee flexes to absorb the forces produced from contact with the ground. The center of mass velocity decreases in the horizontal direction and the kinetic and potential energy increases (Novacheck, 1998). As the runner transitions to midstance, peak knee flexion will occur. The horizontal velocity of the center or mass will increase to prepare the runner for terminal stance/ preswing and the transition into swing phase.

Typically, musculoskeletal injuries occur at initial contact due to the transient, passive impact peak. The passive impact peak results from the vertical ground reaction force that is applied to the leg while the leg is not considered under muscular control (Hamill, 2009). Therefore, the force is thought to be distributed among the non-contractile properties of the leg during this phase and may cause structures such as ligaments to absorb a large percentage of the collision forces produced at initial contact; however, additional research is needed to confirm this idea.

Patellofemoral Pain

Patellofemoral pain (PFP) is one of the most commonly reported running injuries (van Gent, 2007; Taunton, 2002), particularly as the running distance increases (Lopes, 2012). PFP diagnoses are not done with any specific testing, and therefore, definitive diagnosis can be tricky due to the variation in interpretation of knee pain by individuals reporting to clinicians. However for the purpose of this review, it is defined as pain originating from contact of the posterior surface of the patella and the femur. There are other symptoms that have been associated with PFP, including crepitus, catching and giving way, swelling and stiffness (Petersen, 2013; Thomee, 1999); however, the most common complaint is pain during and/or after running. Although PFP is commonly diagnosed in runners, the etiology is relatively unclear (Thomee, 1999), although several factors have been investigated. Readers are directed to previous reviews (Peterson, 2013; Lankhorst, 2012; Barton, 2009; Thomee, 1999) for an in depth analysis of PFP as this review will only give a brief description of the pathophysiology of PFP.

The pathophysiology of PFP appears to multifactorial in nature with several dynamic abnormalities of the lower extremity involved (Petersen, 2013; Lankhorst, 2012; Davis, 2009; Thomee, 1999). Although many mechanisms have been associated with PFP, it is well established that several factors have been consistently linked with PFP. Specifically, thigh muscle imbalances (Lankhorst, 2012; Davis, 2009; Thomee, 1999), patellar maltracking due to functional malalignment or dynamic knee valgus (Petersen, 2013; Thomee, 1999), and overuse (Thomee, 1999) appear to have the strongest evidence as part of the multifactorial causes of PFP.

There have been several interventions suggested for the treatment and prevention of PFP (Petersen, 2013; Lankhorst, 2012; Thomee, 1999), including gait retraining (Rixe, 2012; Davis, 2009). Gait retraining, in its simplest form, is learning how to ambulate again after injury. This concept can be applied to runners with PFP to teach them how to run in such a way that they decrease their risk for developing and exacerbating PFP.

Gait retraining

Gait retraining is a relatively new technique that has been used to correct gait perturbations that lead to injuries in runners, specifically PFP. To our knowledge, the literature is limited on the effects of gait retraining on PFP in runners, however several recent studies have been published.

Noehren and Davis (2009) conducted one of the initial gait retraining investigations. Researchers conducted a case study on two female runners whom presented with a history of PFP. Following gait retraining sessions, they determined that the subjects reduced hip adduction and knee pain. They subsequently followed up with a similar gait retraining study that involved real-time feedback on dynamic knee alignment (Barrios, 2010). Eight subjects with clinical malalignment (tibial mechanical axis ≥ 11°) performed eight gait-retraining sessions while walking on a treadmill at a self-selected pace. Subjects received real-time visual feedback on knee alignment in a fading feedback design. Over-ground gait analysis was performed pre- and immediately post-retraining with a one-month follow-up analysis. Barrios and colleagues reported a 20% average reduction in the knee external adductor moment and an increase of hip internal rotation by an average of eight degrees immediately post- and one-month post-retraining compared to baseline (2010). Their results indicate that gait retraining improved the dynamic knee alignment while walking and that the modified gait was internalized through the retraining sessions. These data are similar to the results of Noehren et al.

(2011), who determined that gait retraining in individuals with PFP using real-time feedback on hip alignment decreased hip adduction immediately post- and one-month after gait retraining using a similar retraining protocol. They also found that pain was significantly decreased immediately post- and one-month post retraining (86% decrease; p = 0.001). Similar results were reached when researchers utilized gait retraining with an increased trunk lean and determined that there was a significant reduction in the peak knee adductor moment and the peak external hip adduction moments (Hunt, 2011). However, subjects reported difficulty in learning the new gait pattern and complained of joint discomfort as a result. Therefore, this protocol, although shown to decrease front plane joint moments, may not be an appropriate recommendation for some individuals.

Crowell & Davis (2011) implemented gait retraining with a protocol similar to those previously described (Barrios, 2010; Noehren, 2011) using subjects with large peak tibial acceleration values. Real-time feedback was provided to the subject through the usage of an accelerometer attached to the distal tibia. Researchers demonstrated that subjects were able to significantly reduce tibial acceleration and vertical force loading with the modified gait immediately post- and one-month post retraining, also concluding that learning occurred through internalization.

Since real-time feedback requires the usage of a motion analysis system and other expensive equipment, another simpler method was tested to determine its effect on gait retraining in runners with PFP. Willy and colleagues (2012) had subjects perform eight gait-retraining sessions with mirror and verbal feedback during treadmill running with a fading feedback design. Researchers determined that there was a significant reduction in peak hip adduction, contralateral pelvic drop, and hip abduction moment during running post-retraining. Additionally, subjects maintained these changes at the one-month and three-month follow-up analyses with reported improvements in pain and function.

Most recently, gait retraining was investigated for its effect on the knee adduction moment and pain (Shull, 2013). Individuals with medial-compartment knee osteoarthritis were subjected to six weeks of gait retraining using real-time feedback. Researchers determined that at the end of the retraining sessions, subjects decreased the knee adduction moment and maintained this decrease one-month post retraining. Subjects also reported improvements in pain and function. However, this study was conducted with subjects walking and therefore, caution should be used when interpreting these data and applying these results to runners.

Collectively, these outcomes demonstrate that gait retraining has been successful in internalizing a modified gait pattern and maintaining changes in measured variables and reported decreases in pain and improvements in function. However, these studies have focused on gluteal and hip mechanics (tibial acceleration for those prone to stress fractures) and have not examined the effects of changing footstrike patterns on pain and function in runners with PFP. Different foot-strike patterns may cause various gait perturbations and may put the runners at risk for other various running-related injuries. A case study reported that switching from RFS to FFS reduced vertical impact peak and rates of loading in addition to reduced knee pain, providing preliminary data to warrant further investigation into gait retraining with foot strike patterns (Cheung, 2011).

Forefoot strike vs. rearfoot strike

A rearfoot strike (RFS) during running is the most common foot strike pattern among runners. It has been reported that upwards of 75% of runners tend to RFS, with approximately 24% using a midfoot strike (MFS) and 1% using a forefoot strike (FFS) gait pattern (Kasmer, 2013; Larson, 2011; Hasegawa, 2007). Typically, researchers either combine MFS and FFS or negate MFS during experimental procedures due to the minor biomechanical differences between them, which can affect interpretation of results. There are many kinematic and kinetic differences between RFS and FFS patterns during running that result in different injury risks (Goss, 2012). This review identifies salient variables that are distinctly different between foot strike patterns.

Kinematics

Many studies have investigated the kinematic differences between FFS and RFS. Most of the differences observed are at initial contact, although there are some different stance phase characteristics possibly resulting from differences in foot contact time (Kulmala, 2013) or in the methodological definition(s) of foot strike pattern.

Classically, foot strike has been determined using a strike index (SI) with the use of a force platform and location of the center of pressure (COP) within the foot at initial contact (Cavanaugh, 1980). RFS was measured as initial contact with 0%-33% of the foot or the posterior third of the foot. Midfoot strike (MFS) was measured as initial contact with 34%-67% of the foot or the middle third of the foot. FFS was measured as initial contact with 68%-100% of the foot or the anterior third of the foot. However, other newer methods have been developed and validated to identify foot strike patterns. Altman and Davis (2012) determined that calculating the foot strike angle was significantly correlated ($R = 0.92$, $p < 0.01$) with the strike index. Researchers reported that the foot strike angle (FSA) was calculated by subtracting the angle of the foot while standing from the angle of the foot at foot strike. The results were that RFS = FSA > 8°, MFS = -1.6° < FSA < 8°, and FFS = FSA < -1.6°. Therefore, usage of FSA is acceptable when there is limited access to a force platform to measure COP. More recently, it was determined that identifying foot strike patterns through measurement of heel and metatarsal accelerations was highly correlated ($R = 0.916$, $p < 0.0001$) with the FSA in the sagittal plane (Giandolini, 2014). Researchers positioned two uniaxial accelerometers on the foot and measured the time between the heel and metatarsal acceleration peaks (THM). Foot strike classification was: FFS < -5.49 ms < MFS < 15.2 ms < RFS. Each method is reliable in identifying foot strike patterns and researchers should choose which method to use based on available equipment in the study location (i.e. laboratory setting versus outdoor running track).

There is a significant difference in ankle angle at initial foot contact with the ground (Kulmala, 2013; Nunns, 2013; Shih, 2013; Williams, 2012;). It has been shown that RFS resulted in ankle dorsiflexion at initial contact while FFS resulted in ankle plantarflexion while running along a 20-m runway at a fixed running speed (Williams, 2012), which is similar to results from a subsequent study that determined that there was increased dorsiflexion in RFS, both barefoot and shod, compared to FFS (Shih, 2013).

Currently, the results shown in the research are equivocal as to whether there is a significant difference in knee and hip angles at initial contact between FFS and RFS patterns (Williams, 2012). While running along a runway at a fixed running speed, researchers determined that there were no significant differences in knee and hip angles at initial contact (Kulmala, 2013; Nunns, 2013; Williams, 2012). Conversely, other researchers (Hall, 2013; Shih, 2013; Lieberman, 2010) have determined that there was a greater degree of knee flexion at initial contact with FFS, while there was a greater amount of hip extension at initial contact with FFS compared to RFS.

Delgado and colleagues (2013) determined that changing runners from RFS to FFS decreased range of motion (ROM) in the lumbar spine, but did not change sagittal plane spine position during running. Similarly, it was determined that knee and ankle ROM was not significantly different between foot strike patterns, although hip ROM was significantly different between the foot strike patterns (Shih, 2013). Conversely, it has been demonstrated that knee ROM was significantly different between RFS and FFS (Nunns, 2013). Very few studies have measured these variables and so far results appear equivocal.

Kinetics

Loading rate (LR) is the speed at which forces are applied to the body. More specifically, it is the slope of the vertical ground reaction force (vGRF) typically defined from initial contact to the first impact peak maximum (Goss, 2013; Shih, 2013). However, there are other methods employed to compute LR, specifically with and without the presence of an impact peak that occurs during RFS and FFS, respectively. Although LR is typically defined from initial contact to impact peak during RFS running, some researchers use only 20% to 80% of the ground contact time leading to the impact peak to compute LR (Goss, 2013; Kulmala, 2013), while others have used a threshold value of 200 N to 90% of the impact peak (Lieberman, 2010). During FFS running, due to the absence of the impact peak, researchers typically use a percentage of stance phase with some using 3% - 12% of stance phase (Goss, 2013) and others using a threshold value of 200 N to 6.2 ± 3.7% of stance phase (Lieberman, 2010). It is not common that

that the same calculation is used to determine LR in RFS and FFS, although it has been done successfully with significant differences between results (Shih, 2013). However, the different methods of calculating LR can influence the results when comparing RFS to FFS due to the varying amount of data that is included. Comparing the differing methodologies for calculating LR is an area of future research that needs to be addressed.

Nevertheless, it appears that a smaller LR is more favorable in terms of injury prevention (Zadpoor, 2011; Milner, 2006). Shih et al. (2013) determined that in both barefoot and shod conditions, FFS pattern resulted in a lesser average and peak-LR compared to RFS. Similarly, it was established that FFS was associated with a smaller LR compared to RFS while running at a fixed speed (Goss, 2013; Kulmala, 2013; Lieberman, 2010).

Shock attenuation during running is the act of absorbing energy due to foot impact with the ground (or contact surface), which reduces the shock wave magnitude between the head and the foot (Mercer, 2003) and varies with running speed (Shorten, 1992), knee flexion angles and different foot contact patterns (Frederick, 1986). It has been shown that RFS had greater shock attenuation compared to FFS (Delgado, 2013). This is likely due to the lesser peak leg impact at contact with FFS, suggesting that use of a FFS decreases shock while running (Delgado, 2013; Hatala, 2013; Hamill, 2011; Lieberman, 2010; Davis, 2009; Squadrone, 2009; Divert, 2005). This is a feasible conclusion as it has been shown that the vGRF and vertical loading rate is significantly smaller in FFS compared to RFS (Kulmala, 2013), and RFS would have increased shock absorption due to the greater stride length (Squadrone, 2009; Mercer, 2003). Stride length may be greater during RFS because there is more cushioning in the shoe underneath the heel, which absorbs some of the impact force experienced with running. There is less cushioning underneath the forefoot, suggesting that the impact forces associated with FFS would not be absorbed by the shoe to the same extent as with RFS. Runners using FFS would then adjust stride length to limit the impact forces experienced during running (Squadrone, 2009).

Knee moments during running with a FFS compared to a RFS have been found to be significantly different (Kulmala, 2013). Specifically, it has been shown that the patellofemoral contact force and patellofemoral stress were significantly less during FFS compared to RFS (Kulmala, 2013). Additionally, the knee abduction moment was significantly smaller during FFS compared to RFS, possibly due to the decreased stride length and subsequent shock absorption associated with FFS (Squadrone, 2009; Mercer, 2003).

However, some recent research has shown that while running at a self-selected speed, runners exhibited greater peak contact forces at the ankle during FFS, but similar peak contact forces at the knee and hip (Rooney, 2013). It was also determined that habitual use of a FFS resulted in increased contact forces at each joint compared to habitual use of RFS and those increased contact forces occurred in the first 40% of stance phase (Rooney, 2013). Similar results were found when several research groups determined that FFS was associated with an increased Achilles tendon force (Almonroeder, 2013; Kulmala, 2013) and plantarflexion moment (Kulmala, 2013; Paquette, 2012). Together, these results suggest that usage of a FFS pattern during running may increase the risk of developing injuries at ankle due to the increased force and loading rate. The anteroposterior component of the GRF during FFS has two impact peaks during the first 40% of stance phase, with the first peak being a transient, increase in force in the negative direction (braking). This peak is similar to the first impact peak in the vGRF component that is evident with RFS and could result in injury. During running with a FFS, an excessive braking impulse may be present which results in increased repetitive tensile forces on the muscles of the posterior lower extremity (Lohman, 2011; Divert, 2005) and may partially explain why an increased Achilles tendon force and plantarflexion moment may increase ankle injury risk (Almonroeder, 2013; Kulmala, 2013; Paquette, 2012).

Muscle Activity

Muscle activity has not been well researched regarding differences between foot strike patterns. However, recently Rooney & Derrick (2013) determined that there was increased gastrocnemius, soleus, and peroneal forces with a FFS during the first half of stance phase, which contributed to the increased contact forces at the ankle. Similar results were found when researchers evaluated the muscle activity of runners using a FFS and RFS while barefoot (Almonroeder, 2013; Shih, 2013) and shod (Shih, 2013).

Running Economy and Performance

Running economy is a measure of how efficiently a person uses oxygen at a given running speed. Therefore, typically, the lower the oxygen consumption (VO_2) at a given running speed, the more efficient the individual. Limited research exists on the variability in running economy between FFS and RFS, however a few studies will be reviewed on the differences between the foot strike patterns.

Gruber and colleagues (2013) investigated the difference in economy while running at three different fixed speeds using FFS and RFS patterns. They determined that runners using their habitual foot strike pattern showed no difference in VO_2 between groups, which is similar to the results of a subsequent study (Di Michele, 2013). However, when running at a fast speed (4.0 m/s), FFS pattern resulted in higher VO_2 compared to the RFS pattern This happened specifically when RFS runners were switched to FFS, suggesting that FFS is not more economical than the RFS when runners switch to a non-habitual foot strike pattern (Gruber, 2013). Similarly, Ogueta-Alday et al. (2014) determined that RFS runners were more economical at various fixed running speeds compared to midfoot strikers. The differences seen in running economy in these studies may be due to the increased muscle activity associated with FFS (Rooney, 2013), which will increase oxygen consumption. To our knowledge, no evidence exists on whether running economy will return to pre-training levels after implementation of a gait retraining protocol switching from RFS to a FFS during running, and remains to be an area of future research.

Cost of transport (CoT) is the energetic cost to travel a given distance and has also been measured for its differences between foot strike patterns. It was determined that there was no significant difference in the CoT between RFS and FFS (Perl, 2012). This suggests that the energy expenditure for a given distance will be the same for a runner using either foot strike pattern, signifying that switching foot strike patterns will not change energy expenditure over a given distance.

Kasmer and colleagues (2013) examined whether there was a difference in performance between footstrike patterns in average runners during a marathon. Among the 1991 runners that were evaluated, they determined that the more elite runners were more likely to use a FFS or midfoot strike and have a better finishing position in the race, likely due to the decreased ground contact time and increased stride frequency associated with FFS (Di Michele, 2013; Nunns, 2013; Hayes, 2012; Hasegawa, 2007; Squadrone, 2009; Divert, 2005). Similarly, it was determined that as running speed increased, the likelihood of FFS or midfoot strike pattern during running increased as well (Hatala, 2013; Hayes, 2012; Hasegawa, 2007). However, other work has shown that there was no significant difference between footstrike patterns and race times (Larson, 2011). This discrepancy in findings may be due to the specific type of race, as one was a qualifier for the Boston marathon (Kasmer, 2013) and the other was not as competitive.

Injury Rates

Before making recommendations regarding usage of foot strike patterns, it is necessary to evaluate the injury rates associated with each. Daoud and colleagues (2012) determined that RFS runners have significantly higher rates of injury from repetitive stress compared to FFS runners. Similarly, it was determined that RFS runners were 3.41 times more likely to report injuries compared to FFS runners (Goss, 2012). Collectively, these studies indicate that FFS reduces the likelihood of injury in runners, and its usage during running is a clinical recommendation that is made to individuals (Lorenz, 2012).

Summary and Future Research

Many runners are affected by PFP and the cause appears to be multifaceted. There have been a number of strategies utilized to aid in decreasing the occurrence and severity of PFP, including gait retraining. Several studies have addressed gait retraining and collectively, the results suggest that it is successful strategy to employ. These studies focused on hip and gluteal mechanics; however, usage of footstrike patterns with gait retraining may be an appropriate alternative due to the benefits associated with FFS compared to RFS. Future research should investigate the effects of gait retraining utilizing footstrike patterns and determine the magnitude of internalization of the new footstrike pattern. Additionally, research should address whether switching from a RFS to a FFS significantly increases pain and/or injuries at the ankle, due to the increased force and loading at the ankle associated with FFS.

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CHAPTER 3

RESEARCH MANUSCRIPT

This chapter presents a research manuscript, entitled "The Effects of Gait Retraining in Runners With Patellofemoral Pain". This manuscript will be submitted to *Medicine and Science in Sport and Exercise*. It is authored by Jenevieve Roper, Elizabeth Harding, Deborah Doerfler, James Dexter, Len Kravitz, Janet Dufek, and Christine Mermier. The manuscript follows the formatting and style guidelines of the journal. References are provided at the end of the chapter.

Title: The Effects of Gait Retraining In Runners With Patellofemoral Pain

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ABSTRACT

Running popularity has increased resulting in a concomitant increase in running-related injuries. Of these injuries, patellofemoral pain (PFP) is the most commonly reported. **PURPOSE:** The purpose of this study is to determine whether gait retraining by modifying footstrike patterns from rearfoot strike (RFS) to forefoot strike (FFS) reduces PFP and improves associated biomechanical measures, and whether the modification results in increased risk of ankle injuries. **METHODS:** Sixteen subjects (n=16) received clearance to participate by a licensed physical therapist, and were randomly placed in the control (n=8) or experimental (n=8) group. Subsequently, the experimental group (EXP) performed eight gait retraining running sessions where footstrike pattern was switched from RFS to FFS, while the control group (CTL) performed eight running sessions with no intervention. Knee flexion (Kflex), knee valgus (Kvalg), and ankle flexion (Aflex) at initial contact, knee (KL) and ankle loading (AL), patellofemoral contact force (PFCF), patellofemoral stress (PFS), Achilles' tendon force (ATF), and knee pain as reported on a visual analog scale (VAS) were recorded pre-, post-, and one-month post-running trials.
RESULTS: In Exp, knee pain was significantly reduced post-retraining (mean Δ, -4.225; $p<0.05$) and at one-month follow-up (mean Δ, -4.276; $p<0.05$). Kflex was significantly increased post-retraining (mean Δ, 6.044°; $p<0.05$). Kvalg was significantly improved post-retraining (mean Δ, 2.782°; $p<0.05$) at one-month follow-up (mean Δ, 4.066°; $p<0.05$). Aflex was significantly different post-retraining (mean

Δ, -23.958°; $p<0.05$), as well as AL post-retraining (mean Δ, 14.738°; $p<0.05$) and one-month follow-up (mean Δ, 17.192°; $p<0.05$). PFCF, PFS, ATF, and KL were not significantly different. **CONCLUSION:** Retraining from RFS to FFS results in significant reductions in knee pain in runners with PFP without increasing risk of ankle injuries.

Keywords: injury, knee, lower extremity, running

Introduction

Recreational running is one of the most popular ways that people regularly exercise and participation numbers have increased dramatically since the 1990's (20). In 2012, more than 15 million people participated in running events (28) compared to 4.6 million participants in the 1990's. The increased number of participants is likely due in part to the numerous reported health benefits associated with cardiovascular exercise (5, 8, 15).

However, as the number of participants in recreational running has increased, there has been a concomitant increase in the number of running-related injuries. It is estimated that somewhere between 20-80% of runners get injured each year (23, 38), with the incidence of injuries being higher in recreational and novice runners (2, 35). Of these, the most commonly reported running-related injury is patellofemoral pain syndrome (PFP), which affects more women compared to men (62% and 38%, respectively) (33, 38). PFP is characterized as pain originating from contact of the posterior surface of the patella and the femur during and/or after running. The pathophysiology appears multifactorial, however, the most common factors associated with PFP are thigh muscle imbalances, patellar maltracking due to functional malalignment or dynamic knee valgus, and overuse (6, 17, 26, 34).

Several interventions have been suggested to alleviate PFP, including patellar bracing, medial posts, and muscle strengthening. However, gait retraining is a relatively new method that has been introduced as a way to potentially limit PFP. Gait retraining is essentially teaching someone how to run with a modified gait pattern by altering his/her running mechanics. Limited research exists on gait retraining; however, the studies that have used gait reeducation protocols similar to the current study have reported significant reductions in knee pain through an internalized gait pattern, which subjects maintained several months after retraining (1, 3, 14, 24-25, 41). However, many of the gait retraining studies have focused on gluteal and hip mechanics, with no studies to date suggesting a change in footstrike pattern as a possible strategy due to the benefits associated with a forefoot strike (FFS) running pattern.

It has been determined that gait pattern is a significant factor for exercise-related lower-leg pain (39), with most runners using a heel strike pattern. Approximately 75% of shod runners naturally run with an initial heel strike (12). It appears to be more comfortable for runners to heel strike because running shoes have thicker cushioning in the rear foot compared to the forefoot. Runners using a rearfoot strike (RFS) have been shown to have a 3.4 times greater risk of sustaining a running-related injury compared to runners who use a forefoot strike (FFS) (4, 10). This is likely due to the greater shock attenuation and loading rate that is associated with RFS (7, 11, 16, 18, 30). Consequently, a larger loading rate is not favorable in terms of development of running injuries (42, 22).

Additionally, it has been determined that FFS is associated with lesser patellofemoral contact force and stress (16), which may potentially reduce PFP. Therefore, it is possible that converting from an RFS to an FFS is more beneficial as it could be associated with a decreased risk of injury. Since there is no vertical impact transient in FFS, this also decreases the risk of developing an injury at impact, especially at the knee. There is an increased reliance on musculature from greater knee flexion being present at impact when runners use a FFS. Therefore, the purpose of the present study was to determine if runners with PFP benefit from gait retraining that modifies their footstrike pattern from RFS to FFS due to the reduction in patellofemoral stress and patellofemoral contact force. A secondary purpose was to determine whether conversion from RFS to FFS resulted in injuries or pain at the ankle as a result of the change in Achilles' tendon forces.

Methods

Participants

An *a* priori power analysis was conducted with GPOWER to determine sample size needed for the present study. Based on the number of variables of interest, α= 0.05, and a power of 0.80, 16 subjects were required. Twenty-one recreational runners participated in this study. Participant characteristics can be found in Table 1. Participants self-reported as runners who RFS and reported having mild to moderate chronic, running-related knee pain that occurred during and/or after they ran. All participants reported that running was included in their regular training regimen. They provided written informed consent prior to participation and the Institutional Review Board of the University of New Mexico approved the protocol.

All potential subjects underwent a physical examination by a licensed physical therapist, similar to the exam used in the study by Souza and Powers (31). The physical exam ruled out any ligamentous instability, patellar tendinitis, and significant knee effusion. Subjects were included if they indicated that their pain level was at least "3" and no more than "7" on a "0" to "10" visual analog pain scale with "0" indicating the absence of pain and "10" meaning the worst pain possible. Additionally, participants were included if they reported pain in the patellofemoral region that occurred during and/or after running, and if pain occurred in one of the following activities: squatting, kneeling, stair ascent/descent, and prolonged sitting. Female subjects took a urine pregnancy test to determine pregnancy status as pregnant subjects were excluded. Subjects were excluded if they had a history of knee surgery on the affected knee, traumatic patellar dislocation, and/or any neurological impediments that would influence gait. Five subjects were excluded as a result of the physical exam. Therefore, 16 subjects (11 females, 5 males) were included in the study.

Instrumentation

Three-dimensional motion analysis was completed using a camera-aided motion analysis system (Vicon MX-20; Oxford Metrics Ltd, Oxford, UK). Data were sampled at 120 Hz. Sixteen reflective markers were placed according to the lower-body plug-in gait model to acquire subject kinetic and kinematic data. All kinetic and kinematic data were subsequently processed using Vicon Polygon (Polygon 4.1, Oxford Metrics Ltd, Oxford, UK).

Protocol

Subjects were randomized to either the control group or experimental group. Randomization was done within sex to ensure equal representation and reduce the likelihood of influence of sex-specific variables. All subjects went through the same procedures with the exception of the experimental group who underwent eight sessions of gait retraining from RFS to FFS. Subjects in the control group were not trained to run with a different technique, but reported to the lab for eight sessions of running equal in time to the experimental group trials. Subjects were included only if they agreed to abstain from any additional running outside of the study during the training phase of the study.

Trained personnel acquired anthropometric measurements before the first running trial. A calibrated scale was used to measure the subjects' weight to the nearest 0.05 kilograms and a stadiometer was used for height to the nearest 0.1 centimeters. Leg length (measured as the distance from ASIS to medial malleolus), and knee and ankle width were measured using a Gulick anthropometric tape and anthropometer, respectively, as required for the Vicon Plug-In Gait model.

Eligible subjects then performed a running trial (described below) in the Gait Analysis Lab at the University of New Mexico. Subjects in both groups were given a new pair of neutral running shoes (Brooks Defyance; Brooks Sports Inc, Seattle, WA, USA), which were used for the duration of the study. No orthotic devices were allowed. New running shoes were given to each subject to minimize gait perturbations associated with different types of shoes and wear patterns that occur over time.

Running Trial

Sixteen, 14 mm reflective markers were placed according to the lower-body Plug-In gait model (Vicon, Oxford, UK). Markers were placed in the following anatomical locations, bilaterally: anterior superior iliac spine, posterior superior iliac spine, lateral mid-thigh, lateral knee, lateral mid-shank, lateral malleolus, on the shoe over the posterior calcaneous, and on the shoe over the head of the second metatarsal. Subjects practiced running across the force platforms at the same speed that was used for the treadmill run so that the foot of the affected limb landed completely on one of the three force platforms. Velocity was controlled using a metronome (Meideal M50; Shenzhen Meideal Musical Instruments Co., Ltd, Shenzhen, Guangdong, China). After several successful practice trials, data collection started. Data were collected for 10 successful passes across the force plate during the trial to a maximum of 15 passes. After completion of the data collection trial, subjects were scheduled for the eight gait training sessions.

Training Sessions

Eight subjects (experimental group) performed eight gait retraining sessions in the Exercise Physiology Lab at the University of New Mexico over a two week period, while the control group (n=8) performed eight running sessions without the intervention. The eight gait retraining sessions took place on a treadmill (Precor 966i; Precor Inc, Woodinville, WA, USA) in front of a mirror as previously described by Noehren et al. (18). Run time started at 15 minutes and gradually increased to 30 minutes. Using methods described by Willy et al. (41) for the experimental group, mirror feedback and scripted statements, such as “run on your toes” and/or “run on the balls of your feet” were used. If necessary, subjects received additional feedback, such as detailed verbal instructions on how to accurately perform forefoot strike running. During the first four sessions subjects were given continuous feedback. During the last four sessions, the feedback was gradually removed (25). At the end of each training session, subjects reported effort of execution and naturalness of the foot strike pattern on a scale of “1” to “10” with “1” being very hard to execute/unnatural and “10” being easy execution/natural (7). Perceived pain was also assessed after each of the training session using a 10 cm visual analog scale.

The control group also performed eight training sessions that comprised of the same amount of volume (15 minutes gradually increasing to 30 minutes). The subjects also ran in front of a mirror, but did not receive any verbal feedback that aided in modifying their running pattern. They also assessed their pain, effort of execution, and naturalness using the same visual analog scale as the experimental group.

Once the training phase was completed for each subject, they performed an identical post running testing session as was done pre-training. Subjects in the experimental group were instructed to use the new running technique during this post-testing protocol. Following the post-test, all subjects were permitted to return to their normal running regimen using the modified footstrike pattern (experimental group) or their normal footstrike pattern (control group). Running trials were performed again at one-month after the post-testing. All subjects used the same speed/pace for the post-testing and one-month follow-up running trials as was used during the pre-testing running trials.

Measurements

The variables of interest included: knee valgus at initial contact, knee flexion at initial contact and loading, ankle flexion at initial contact and loading. Knee and ankle loading, for the present study, were defined as the range of motion that each joint went through from initial contact to the end of the loading response (peak flexion at 10-15% of gait cycle). Peak patellofemoral stress (16), Achilles tendon force (29), and patellofemoral contact force (13) were also measured at the end of the loading response.

Marker trajectories were filtered using a Woltring Filter with a cutoff frequency of 12 Hz. At least eight up to a maximum of 10 successful ground contacts of the foot on the affected limb were selected for analysis. Kinetic and kinematic analyses were performed using the Plug-In Gait model (Vicon Nexus 1.8.2, Oxford Metrics, UK).

Patellofemoral joint contact force (PFCF) was measured during running as described in the model by Ho et al. (13). It is estimated as a function of knee extensor moment (M_k) and knee flexion angle (x). Initially, the moment arm of the quadriceps muscle (L_q) was calculated as a function of knee flexion angle using the nonlinear equation reported by van Eijden et al. (37):

$$L_q = 8.0E^{-5}x^3 - 0.013x^2 + 0.28x + 0.046 \qquad [1]$$

The quadriceps force (F_q) was calculated according to Kulmala et al. (16):

$$F_q = M_k/L_q$$

Then, PFCF was calculated as follows:

$$PFCF = F_q k$$

Similar to Kulmala et al. (16), the constant *k* was estimated based on the knee joint position using an equation based on the data of van Eijden et al. (36):

$$k(x) = (4.62E^{-1} + 1.47E^{-3}x^2 - 3.84E^{-5}x^2)/(1 - 1.62E^{-2}x + 1.55E^{-4}x^2 - 6.98E^{-7}x^3)$$

[2]

Patellofemoral stress (PFS) was calculated as follows (16):

$$PFS = PFCF/\text{contact area}$$

Contact area was calculated according to Ho et al. (13) based on the data of Powers et al. (27) (83 mm^2 at 0°, 140 mm^2 at 15°, 227 mm^2 at 30°, 236 mm^2 at 45°, 235 mm^2 at 60°, and 211 mm^2 at 75° of knee flexion).

Achilles tendon force (ATF) was calculated similar to Kulmala et al. (16) by dividing the plantarflexion moment (M_a) by the estimated Achilles tendon lever arm (L_a) described by Self & Paine (29):

$$ATF = M_a/L_a$$

$$L_a = -0.5910 + 0.08297a - 0.0002606a^2 \quad [3]$$

where a = ankle angle.

Statistical Analysis

A mixed model ANOVA was used to measure the mean differences between the groups for the variables of interest (knee valgus and flexion angle at initial contact, knee loading, ankle flexion at initial contact, ankle loading, patellofemoral stress, patellofemoral contact force, and Achilles tendon force). Tukey's pairwise comparisons were used to determine the differences among pre-, post-, and follow-up testing. Additionally, males and females were compared to determine sex differences in each variable. Statistical analyses were performed using SPSS statistical software (ver 22, SPSS Inc, Chicago, IL, USA) and the alpha level was set *a priori* at $\alpha<0.05$.

Results

Kinetic and Kinematic Variables

Following retraining, it was determined that there were significant interaction effects of time and group on knee flexion angles at initial contact ($F= 4.622$; $p=0.020$, Figure 1, Table 2), knee valgus angles at initial contact ($F=4.921$; $p= 0.016$, Figure 1, Table 2), ankle flexion angles at initial contact ($F= 14.516$; $p<0.001$, Figure 1, Table 2), and ankle loading ($F= 8.864$; $p=0.001$, Figure 1, Table 2). Specifically, post-retraining, the experimental group increased knee flexion angles (mean Δ, 6.044°), while the control group did not significantly change from baseline. Knee valgus angles at initial contact did not significantly change from baseline in the control group, while the experimental group significantly improved knee valgus angles post-retraining (mean Δ, 2.782°) and maintained the changes at one-month follow-up (mean Δ, 4.066°). Ankle flexion angles (dorsiflexion/plantarflexion) were significantly changed in the experimental group (mean Δ, -23.958°) and were maintained at the one-month follow-up, while the control group did not significantly change at either time point. Ankle loading was significantly increased in the experimental group post-retraining (mean Δ, 14.738°) and maintained at the one-month follow-up (mean Δ, 17.192°).

There were no significant interaction effects of time and group in PFS, PFCF, ATF, and knee loading after retraining, although of these variables trended ($p=.106$, $p= 0.100$, $p=0.051$, $p= 0.067$, respectively) trended towards significance.

Pain

Following retraining, it was determined that there was a significant interaction effect of time and group on pain levels as reported on the VAS scale ($F= 5.003$; $p= 0.031$, Figure 2, Table 2). Specifically, both groups reduced pain from pre-training; however, the experimental group had greater reductions in their pain levels (mean Δ, -4.225 vs. -1.725) and maintained the reduction one-month post-retraining (mean Δ, -4.276 vs. -0.457).

Subjects in the experimental group reported calf soreness during the retraining phase. However, this subsided by session six for all of the subjects in the group. Additionally, all subjects reported that their new gait pattern felt natural by session six. Only two subjects in the experimental group reported ankle soreness associated with the new running gait at the one-month follow-up. Subjects described it as an ache that quickly went away after they discontinued running. Both subjects indicated that it only occurred after they ran more than four miles in a single session and that it did not prevent them from continuing to run.

Male vs. Female

It was determined that gender only had a significant effect on knee loading (F= 3.981, p= 0.32, Figure 3). Males in the experimental group reduced their knee loading significantly more compared to males in the control group (mean ROM, 26.296°, 95% CI, 21.666° to 30.926°; mean ROM, 33.930°, 95% CI, 28.260° to 39.601°, respectively) while female knee loading was equivocal between groups.

Discussion

The primary purpose of this study was to determine the effects of gait retraining by modifying footstrike patterns from RFS to FFS in runners with PFP. Primarily, subjects reported significant reductions in PFP, compared to the control group, after retraining to a FFS running gait. We also determined that this reduction in pain was likely associated with the reduction in knee valgus angles and increase in knee flexion angles at initial contact, with a lesser association to PFS and PFCF. To our knowledge, this was the first study that examined gait retraining with footstrike patterns and determined that switching from RFS to FFS reduced reported PFP.

Kinetics and Kinematics

It is well known that gait retraining has led to significant changes in measured kinetics and kinematics. Noehren and Davis (24) were among the first investigators of gait retraining in runners with PFP to report significant reductions in hip adduction post-retraining. Subsequently, numerous investigators have determined that gait retraining has led to changes in hip adduction (14, 25, 41), as well as other variables, such as knee external adductor moment (1), and tibial acceleration and vertical loading force (3). Although these studies focused primarily on hip mechanics, the present study adds to the current literature, as we determined that there were significant increases in knee flexion and ankle plantarflexion at initial contact, and ankle loading post-retraining, as well as reductions in knee valgus angles at initial contact leading to greater knee varus.

We determined that the most important change as a result of the retraining was the reduction in knee valgus angles at initial contact with FFS, since it has previously been identified that dynamic knee valgus contributes to PFP (26, 34). In the experimental group, knee valgus angles decreased on average 2.782° post-retraining and 2.5° at the one-month follow-up, while the control group did not change from baseline. To our knowledge, limited studies exist on the difference in knee valgus angles between RFS and FFS. Nevertheless, in theory, the reduction in knee valgus angles at initial contact is feasible since it has been determined that there is a smaller knee abduction moment, PFS, and PFCF with FFS (16). The present study showed trends towards reduced PFCF and PFS, which likely resulted in reduced knee valgus. The reduction in these variables is likely associated with shorter stride length and lesser shock absorption (21, 32).

Experimental subjects increased knee flexion at initial contact on average six degrees post-retraining, which is consistent with previous research which determined that FFS lead to greater knee flexion compared to RFS, both barefoot (21.31±5.08° vs. 17.41±4.93°) and shod (23.71±5.07° vs. 14.25±4.60°) (30). This is likely due to the shorter stride length that is associated with FFS (21, 32). The shorter stride length likely results in reduced knee extension, as the heel is no longer initially contacting the ground. Additionally, ankle plantarflexion was increased on average ~24° for the experimental group post-retraining, and the increase was maintained at the one-month follow-up (mean Δ, 25°). This is consistent with previous research that determined that RFS results in greater dorsiflexion at initial contact and FFS results in greater plantarflexion at initial contact (30, 40).

Ankle loading, as measured by ankle ROM from initial contact to he end of the loading response, was previously determined to have no significant differences between RFS and FFS (30), however, the present study determined that there was a significant difference in ankle loading when switching footstrike patterns. This is expected as the initial foot contact is in a different position with FFS; therefore, the ROM that the ankle goes through to the end of the loading response should be greater.

Previously it was shown that acute transition from RFS to FFS resulted in reduced PFS (-1.9 MPa; $p= 0.041$) and PFCF (mean Δ, -0.82 BW; $p= 0.029$), as well as an increase in ATF (1.2 BW; $p= 0.002$) (16). Conversely, in the current study, we did not measure a significant difference in PFCF, PFS, or ATF between the groups, however, we did measure trends associated with all three variables ($p= 0.10$, $p=0.106$, and $p=0.51$, repectively) that were similar to the findings of previous research (16). This finding was somewhat surprising as we hypothesized that the reduction in the knee valgus was likely due to reductions in PFCF and PFS. It is possible that the disparity in results is associated with the running velocity as the present study used a controlled, self-selected running speed. A metronome was set to the preferred pace prior to training to maintain velocity throughout each running pass in the trials and subjects were required to make foot contact simultaneously with each beep. It has been established that RFS have a greater stride length and lower stride frequency compared to FFS at the same running speed (9). The inability of the subjects to increase stride frequency after switching to FFS due to the velocity being controlled by a metronome likely led to shock attenuation values similar to

RFS, resulting in no significant difference for our selected kinetic variables. However, ATF was very close to reaching significance (p=0.051). This result is very similar to previous research, which determined that there was a significant increase in ATF when making an acute transition from RFS to FFS (16). Specifically, it was reported there was an average increase of 1.2 BW in ATF, while the present study reported an average increase of 1.3 BW. We speculate that the increased ATF in the experimental group is strongly associated with greater energy absorption at the ankle throughout the loading response as evidenced by a lesser ground reaction force (18).

Pain

Reductions in pain as a result of gait retraining have been well documented (24-25, 41). Specifically, Noehren and colleagues (25) demonstrated an 86% reduction in PFP, and associated the reduction in pain to reduced hip adduction. Similarly, it was also determined that runners significantly reported reduced pain as a result of gait retraining, which was associated with reductions in peak hip adduction moments (41). In the present study, subjects reported a significant reduction in reported pain (mean Δ, 80%) as a result of retraining. However, since our variables of interest were associated at the knee and ankle, we believe this is attributed to the measured reduction in the knee valgus angle, likely as a result of trends towards lesser PFCF and PFS, which has been reported as a contributor to PFP.

Although it was reported as mild, two subjects did report a mild ache in their ankles at the one-month follow-up trial. They reported this pain as transient and indicated that it did not prevent them from running with the modified running gait. We believe that these two subjects may have experienced ankle pain as a result of increased ATF, as the two subjects who reported ankle pain as a result of FFS had the highest measured ATF of the study. Although it was not statistically significant, increased contact forces at the ankle may be the source of the transient pain. The forces could result in ankle injury if there is an excessive braking impulse, which increases repetitive tensile forces on muscles of the lower extremity (9, 19).

Male vs. Female

In the present study, we determined that there were significant gender effects in knee loading. To our knowledge, no previous research has compared males and females in regards to PFP and measured variables. Therefore, we speculate that the presence of a gender effect in these variables is likely due to limited male subject enrollment (n=5) compared to females (n=11). Future studies should ensure equal male and female population in the study population to reduce the presence of a gender effects on certain variables.

Limitations

One limitation to the current study was the sample size. Although an *a priori* power analysis determined the number of subjects used in the current study to reach the desired power was adequate, several variables were trending towards statistical significance and likely would have showed significant differences with several more subjects. The follow-up period is another possible limitation to the present study. We followed subjects for one-month post retraining, however, it would have been beneficial to do multiple follow-ups over a longer period of time to determine whether the experimental subjects sustained their modified gait pattern without any associated injuries. Additionally, our sample population consisted of more female than male participants. Therefore, it is possible that some variables were influenced by differences between males and females, such as quadriceps to hamstrings ratio, Q-angles, etc. Future studies would benefit by controlling male and female subject enrollment more precisely. Similar to others, we averaged at least eight trials for each subject of data that was normalized, which may lead to underestimation of certain variables. It is possible that the subjects were trying to lunge to reach the force platforms during the over-ground running portion of the trials, which resulted in altered running mechanics. Therefore, the subjects in the present student could have benefited from more practice and better instruction during the over-ground running, to avoid unnatural running mechanics. Additionally, a large number of variables were compared between groups and over time, which may affect the type 1 error rate. Lastly, we required subjects to maintain velocity by making foot contact simultaneously with the tone of a metronome for the pre-, post-, and follow-up trials. This resulted in no change in stride frequency and likely affected our kinetic variables. Future studies would benefit from using a timing system with lights to control velocity to reduce the possible influence the metronome had on kinetic variables.

Summary

The findings of the present study suggest that gait retraining by transitioning from RFS to FFS results in significant increases in knee flexion, knee valgus, ankle plantarflexion, and ankle loading, as well as significant improvements in reported pain. This also suggests that use of a FFS running gait may reduce running-related knee pain. Although, there was lack of a significant increase in ATF, it should be noted that there may potentially be an increase in risk of ankle injuries. Future retraining studies that transition RFS to FFS are needed to determine this outcome.

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Conflict of Interest

The authors of this study have no conflicts of interest to disclose. The results of the present study do not constitute endorsement by ACSM.

Tables and Figures

Table 1. Mean (SD) subject characteristics

	Control (n=8)	Experimental (n=8)
Age (yrs)	21.5 (1.78)	24.63 (5.58)
Height (cm)	166.2 (8.22)	160.73 (5.42)
Weight (kg)	63.92 (10.36)	61.46 (10.79)

Parameters	**Control (n=8) Pre**	**Post**	**Follow-Up**	**Experimental (n=8) Pre**	**Post**	**Follow-Up**	***P* value**
Kinematics							
Knee Flexion at Initial Contact (°)	12.33 (4.13)	11.35 (5.86)	10.86 (5)	10.20 (5.33)	16.25 (3.64)	13.26 (6.59)	.016*
Knee Flexion Max (°)	39.19 (3.98)	36.78 (5.07)	37.42 (7.41)	38.28 (5.31)	37.98 (4.87)	38.62 (7.53)	.679
Knee Loading (°)	27.24 (5.50)	25.91 (5.36)	27.5 (7.34)	28.07 (3.23)	21.95 (5.95)	25.36 (4.17)	.061
Knee Valgus at Initial Contact (°)	-4.23 (3.13)	-4.29 (3.29)	-3.83 (3.51)	-3.28 (3.46)	-0.50 (4.89)	0.78 (4.56)	.016*
Ankle Flexion at Initial Contact (°)	3.44 (8.19)	1.97 (9.13)	-0.17 (7.79)	8.11 (7.21)	-15.85 (5.88)	-17.25 (4.45)	.000*
Ankle Flexion Max (°)	17.49 (5.28)	14.05 (6.38)	14.94 (4.46)	18.03 (3.63)	12.26 (5.26)	12.98 (5.75)	0.756
Ankle Loading (°)	17.45 (5.63)	19.35 (8.67)	20.05 (6.74)	14.53 (4.24)	29.27 (6.85)	31.72 (4.59)	.000*
Kinetics							
Knee Extensor Moment at Initial Contact (N*m/kg)	-0.78 (.39)	-0.63 (.21)	-0.65 (.20)	-0.66 (.14)	-0.62 (.35)	-0.84 (.36)	0.538
Knee Extensor Moment at Max (N*m/kg)	1.89 (.80)	1.5 (.32)	1.98 (1.01)	1.31 (.50)	0.07 (.46)	0.57 (.58)	.019*
Plantarflexor Moment at Initial Contact (N*m/kg)	-0.11 (.10)	-0.22 (.11)	-0.19 (.11)	-0.12 (.06)	0.02 (.32)	-0.22 (.24)	0.306
Plantarflexor Moment at Max (N*m/kg)	1.10 (.61)	0.39 (.29)	1.18 (.83)	0.66 (.39)	1.07 (.62)	1.04 (.67)	.018*

PFCF (BW)	1.69 (1.18)	1.26 (1.04)	1.62 (1.22)	1.81 (.85)	1.31 (.83)	1.37 (1.15)	0.091
PFS (MPa)	6.13 (3.22)	5.49 (4.57)	6.09 (4.44)	9.11 (4.77)	5.64 (3.64)	5.89 (4.99)	0.254
ATF (BW)	1.26 (.67)	1.16 (2.07)	1.88 (1.22)	.88 (.35)	1.69 (2.21)	1.21 (1.62)	0.148
VAS Pain Score	4.41 (1.41)	2.69 (1.94)	3.96 (1.64)	5.26 (1.49)	1.04 (1.09)	.99 (.89)	.022*

Table 2. Mean (SD) kinetic and kinematic data for control and experimental group
BW, body weight; * denotes significance at the 0.05 level

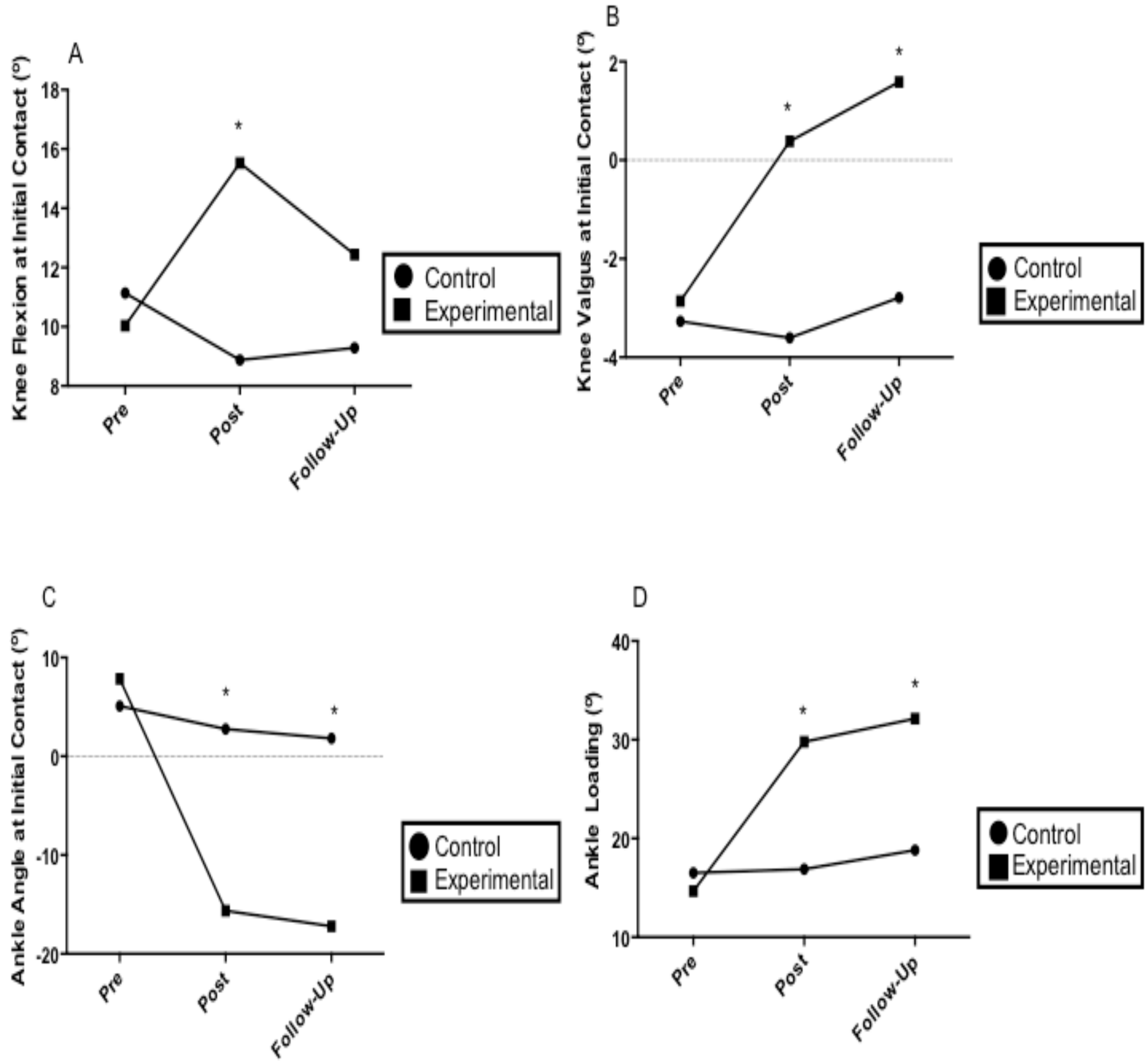

Figure 1. Knee and Ankle Kinematics; ROM- range of motion

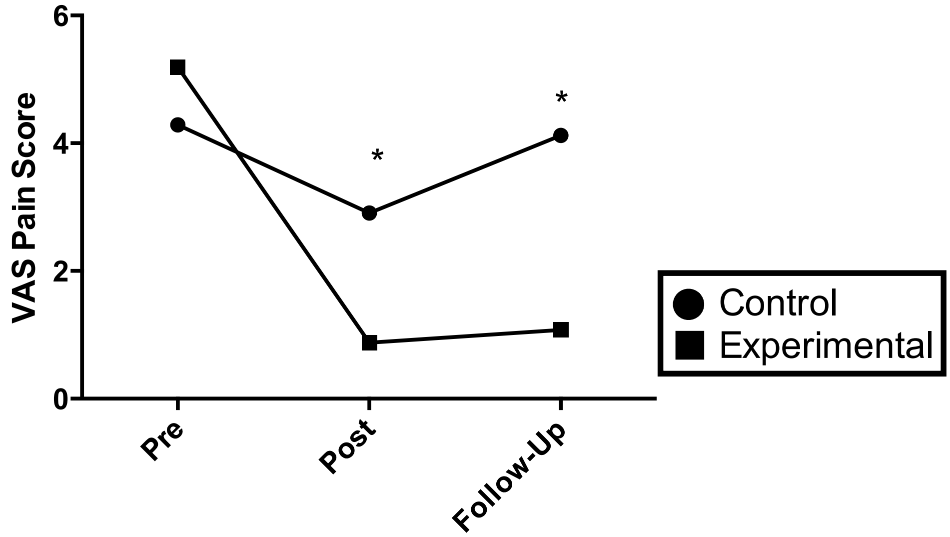

Figure 2. Mean VAS Pain Score

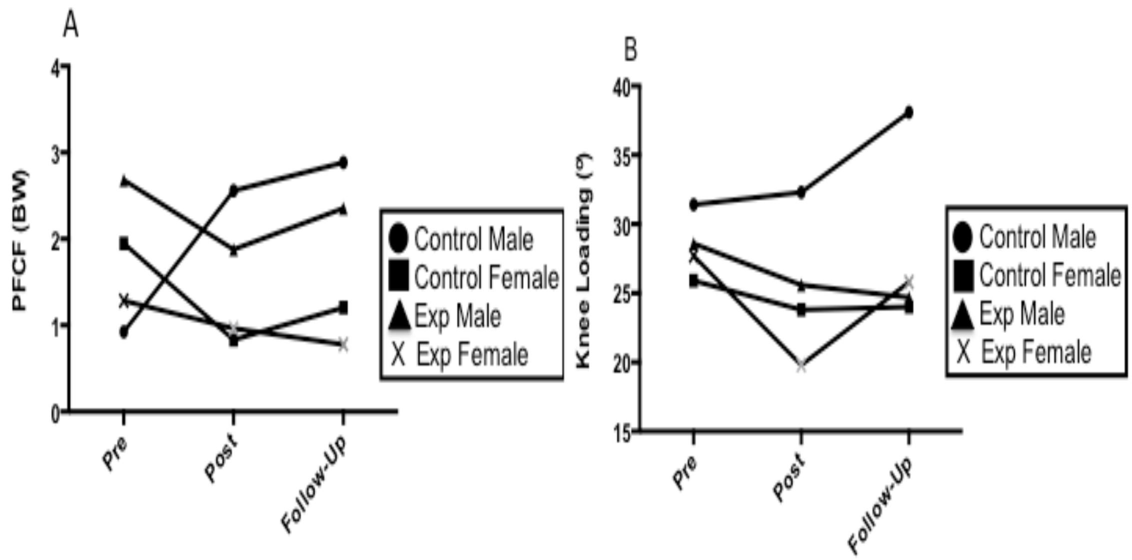

Figure 3. Male vs. Female effects

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CHAPTER 4

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The review manuscript entitled “The Effects of Gait Retraining in Runners With Patellofemoral Pain: A brief review” added new insights into possible management and/or prevention of patellofemoral pain in recreational runners. It is known that gait retraining has been used to accomplish this same outcome. However, previous research did not use footstrike patterns as an intervention. The review paper focused on footstrike patterns (rearfoot strike vs. forefoot strike) as an alternate way to modify running gait and reduce and/or prevent patellofemoral pain (PFP). The manuscript discussed the biomechanical differences between each of the footstrike patterns that ultimately lead to different rates of injury for runners whom use the associated running gait. Further, the manuscript highlighted the performance differences associated with each footstrike, and recommended that runners who rearfoot strike (RFS) and are affected by PFP may benefit from retraining to use of a forefoot strike (FFS).

The research manuscript entitled “The Effects of Gait Retraining in Runners with Patellofemoral Pain” provides evidence that two weeks of retraining to FFS in recreational runners with PFP led to significant improvements in reported knee pain and maintained the reductions in pain one-month after returning to their normal running regimen. The mechanism may be through reduced dynamic knee valgus due to reductions in patellofemoral stress and patellofemoral contact force. In addition, the research shows that there was no significant increase in Achilles’ tendon force (ATF), albeit a trend towards significance was present. Nonetheless, only two subjects reported a mild, transient ankle pain associated with longer runs, which did not prevent them from running or shorten the distance of their runs. The reduction of PFP in affected runners through retraining to FFS has never been shown. In addition, this was the first study to show that retraining to FFS did not cause any significant ankle injuries due to an increase in ATF.

Additionally, running economy data were collected and will be included in an additional manuscript, which will be submitted for publication. VO2 was collected during each running trial to determine whether the modification in running gait changed subsequent running economy. A mixed model ANOVA determined that there was no significant difference in running economy at any time point between the groups ($F= 1.417$, $p= 0.259$). The following figure will be included in the future write up.

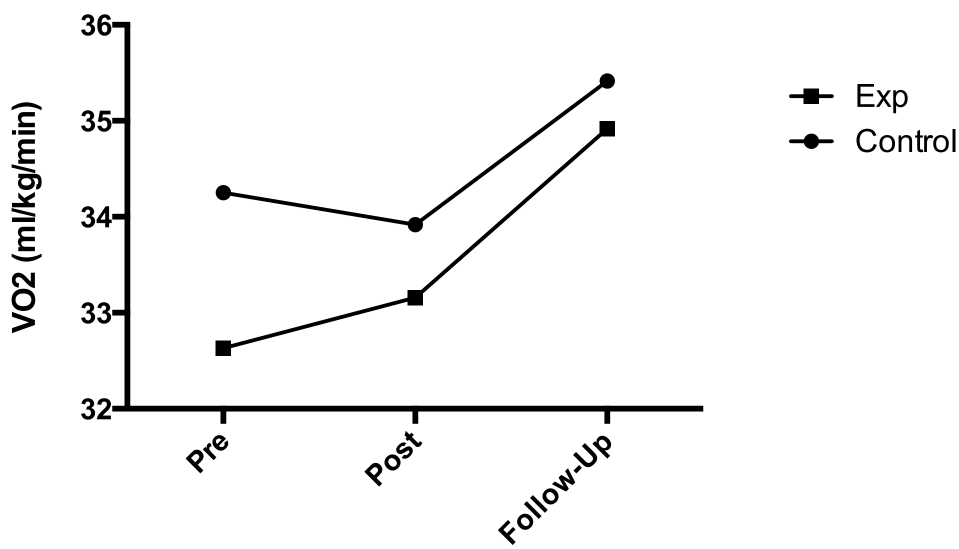

Figure 1. Running Economy

Conclusions

The significant findings of this research were (1) two weeks of gait retraining significantly reduced reported pain in runners affected by PFP, (2) the cause of the reduction in reported pain is possibly due to the reduction in dynamic knee valgus, and (3) retraining to a FFS does not change running economy.

Recommendations

It is possible that a longer follow-up period post-retraining would have improved this research. This would provide evidence of injuries that arise from using the modified running gait after using it longer than one month. Using a light timing system compared to a metronome in the running trials would allow subjects to alter stride frequency adequately for the new running gait. This would allow for proper stride adjustments that normally occur when switching footstrike patterns to give a clearer picture of whether running kinetics also change as has been previously shown.

It is recommended that future studies examine (1) a longer follow-up period post-retraining to determine if new injuries arise as a result of retraining to FFS, (2) the use of a more homogenous sample population in order to better show whether sex affects certain variables, and (3) the effects of switching to FFS on hip kinetics and kinematics and the impact they may have on PFP.

APPENDICES

A. Combined HIPPA and Informed Consent

B. Flyer

C. Health History Questionnaire

D. Retraining Forms

E. Follow-Up Questionnaire

APPENDIX A

The University of New Mexico Combined Consent / HIPAA Authorization to Participate in Research

Introduction

You are being asked to participate in a research study that is being done by Christine Mermier who is the Principal Investigator and Jenevieve Roper, from the Department of Health, Exercise, and Sports Sciences. This research is studying the effects of modifying running technique on pain severity/occurrence.

You are being asked to participate in this study because you are a recreational runner between the ages of 18 and 44 with chronic knee pain that occurs during and/or after running. You are free of any other leg problems as well as any heart or lung problems. Sixteen people will take part in this study at the University of New Mexico.

This form will explain the research study, and will also explain the possible risks as well as the possible benefits to you. We encourage you to talk with your family and friends before you decide to take part in this research study. If you have any questions, please ask one of the study investigators.

What will happen if I decide to participate?

If you agree to participate, the following things will happen:

*You will be asked to sign this informed consent/HIPAA authorization form prior to starting the study.

*You will come to the Gait Analysis Lab on north campus, HSSB 168, for the first running trial. During this time you will fill out a health questionnaire, receive an assessment by a physical therapist, and be given a new pair of running shoes to use for the duration of the study.

*You will be equipped with several reflective markers, which will be placed on your lower body.

*You will then complete several passes across a runway while we record your running with a motion analysis system.

*You will be equipped with a mouthpiece and nose clip. You will run for 10 minutes while we collect the gases you breathe.

*Twenty-four hours after you complete this running trial, you will come to our Exercise Physiology lab in Johnson Center, B143 to perform the training sessions. During this time you will run for about 10-30 minutes in front of a mirror and receive feedback from the research team.

*You will perform these training sessions eight times over two weeks.

*Twenty-four hours after your last training session, you will perform another follow-up running trial, which will be the same as the first trial.

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*After completing the second running trial, you will be allowed to return to your normal running routine for about one month.
*After one month, you will return to the Gait Analysis lab to perform a final running trial, which will be the same as the first and second running trials.

How long will I be in this study?
Participation in this study will take a total of 7 hours over a period of 6 weeks. The initial session will last about 1 hour. The 8 training sessions will last about 10 to 30 minutes and will take place over 2 weeks. There will then be a follow up running trial that will be performed 24 hours after the last laboratory training session.

What are the risks or side effects of being in this study?
There are minimal risks associated with this study. There is a risk of experiencing physical discomfort while running across the runway and while running on the treadmill. There is a possibility that the training sessions may worsen your knee pain, however, there is a small possibility that it could improve. Additionally, there is the possibility of discomfort from the mouthpiece and nose clip, as well as skin irritation from the reflective markers that you are equipped with since they use an adhesive to stick to you. There are risks of stress, emotional distress, inconvenience and possible loss of privacy and confidentiality associated with participating in a research study.
For more information about risks and side effects, ask the investigator.

What are the benefits to being in this study?
There is no direct benefit to you from participating in this study. However, it is hoped that information gained from this study will help reduce chronic, running-related knee pain in recreational runners. Additionally, you are able to keep the running shoes that are given to you for the duration of the study.

What other choices do I have if I do not want to be in this study?
You have the option not to take part in this study. There will be no penalties involved if you choose not to take part in this study.

How will my information be kept confidential?
The consenting process and procedures will take place in a private room in both the Gait Analysis lab and the Exercise Physiology lab. Only the research team will be present during these times. You will be given a unique subject ID, which will be used to identify all your information. The list of subjects and their codes will be kept in the office of Christine Mermier, which will be separate from all other information that may be used to identify you.

We will take measures to protect the security of all your personal information, but we cannot guarantee confidentiality of all study data.
Information contained in your study records is used by study staff and, in some cases it will be shared with the sponsor of the study. The University of New Mexico Institutional Review Board (IRB) that oversees human subject research and/or other entities may be permitted to access your records. There may be times when we are required by law to share your information. Your name will not be used in any published reports about this study.
Information collected as part of the study will be labeled with your initials and a study number; Information (without your name) will be entered into a computer database/locked file cabinet in the Gait Analysis lab, which is only study personnel can access. Christine Mermier and the research team will have access to your study information. Data will be stored for 5 years and then will be destroyed.
Finally, you should understand that the investigator is not prevented from taking steps, including reporting to authorities, to prevent serious harm of yourself or others.

What are the costs of taking part in this study?
There are no costs associated with taking part in the study. However, if you do not have a UNM parking pass, you may have to pay for parking in order to come to campus and participate in the study.

Will I be paid for taking part in this study?
In return for your time and the inconvenience of participating in this study, you will be able to keep the new running shoes that are given to you for use in the study. Compensation is considered taxable income. Amounts of $600 or more will be reported by UNM to the Internal Revenue Service (IRS).

How will I know if you learn something new that may change my mind about participating?
You will be informed of any significant new findings that become available during the course of the study, such as changes in the risks or benefits resulting from participating in the research or new alternatives to participation that might change your mind about participating.

Can I stop being in the study once I begin?
Your participation in this study is completely voluntary. You have the right to choose not to participate or to withdraw your participation at any point in this study without affecting your future health care or other services to which you are entitled. If you are injured at any point during the study, the PI and research team will withdraw you from the study. Your data may still be included in the data analysis up to which point you withdraw. However, if you do not want your data included, contact the PI and inform them of your decision to not include the data in data analysis.

HIPAA Authorization for Use and Disclosure of Your Protected Health Information (HIPAA)

As part of this study, we will be collecting health information about you and sharing it with others. This information is "protected" because it is identifiable or "linked" to you.

Protected Health Information (PHI)

By signing this Consent Document, you are allowing the investigators and other authorized personnel to use your protected health information for the purposes of this study. This information may include: age, height, weight, body fat percentage, weekly mileage, and results of the initial physical therapy assessment.

In addition to researchers and staff at UNM and other groups listed in this form, there is a chance that your health information may be shared (re-disclosed) outside of the research study and no longer be protected by federal privacy laws. Examples of this include disclosures for law enforcement, judicial proceeding, health oversight activities and public health measures.

Right to Withdraw Your Authorization

Your authorization for the use and disclosure of your health information for this study shall not expire unless you cancel this authorization. Your health information will be used or disclosed as long as it is needed for this study. However, you may withdraw your authorization at any time provided you notify the UNM investigators in writing. To do this, please send letter notifying them of your withdrawal to:

Christine Mermier
MSC04 2610
1 University of New Mexico
Albuquerque New Mexico 87131

Please be aware that the research team will not be required to destroy or retrieve any of your health information that has already been used or shared before your withdrawal is received.

Refusal to Sign

If you choose not to sign this consent form and authorization for the use and disclosure of your PHI, you will not be allowed to take part in the research study.

Whom can I call with questions or complaints about this study?

If you have any questions, concerns or complaints at any time about the research study, contact the PI Christine Mermier at cmermier@unm.edu and/or (505) 277-2658

If you need to contact someone after business hours or on weekends, please call and ask for Jenevieve Roper, (505) 379-4524.

If you would like to speak with someone other than the research team, you may call the UNM Office of the IRB at (505) 277-2644.

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Whom can I call with questions about my rights as a research participant?
If you have questions regarding your rights as a research participant, you may call the UNM Office of the IRB (OIRB) at (505) 277-2644. The IRB is a group of people from UNM and the community who provide independent oversight of safety and ethical issues related to research involving human participants. For more information, you may also access the OIRB website at http://irb.unm.edu/.

CONSENT AND AUTHORIZATION
You are making a decision whether to participate in this study. Your signature below indicates that you read the information provided (or the information was read to you). By signing this consent form, you are not waiving any of your legal rights as a research participant.
I have had an opportunity to ask questions and all questions have been answered to my satisfaction. By signing this consent form, I agree to participate in this study. A copy of this consent form will be provided to you.

____ ________________________
____________________ Name of Adult Subject (print)

____
____
Signature of Adult Subject Date

APPENDIX B

Recreational Runners Needed for Running Study at UNM Gait Analysis Laboratory

What is the study about? Different running strategies and how they affect the pain levels in runners with chronic knee pain.

Who can volunteer? Healthy recreational runners 18-44 years old who meet the following conditions:
•Must always run in shoes
•Must always heel strike when running
•Have a history of chronic knee pain for the last 6 months
•Have not had any lower extremity injury within the past 6 months

Test sessions: 11 visits to the Gait Analysis lab on north campus and the Exercise Physiology lab in Johnson Center. Each visit will last about 10-90 minutes. You will be running at a self-selected pace during each session.

Will I be paid? No, but you will be given a new pair of running shoes which you may keep.

Who can I contact for more information?
Jenevieve Roper, 505-277-2658, jlroper@unm.edu

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APPENDIX C

Health Questionnaire/Data Sheet

Subject ID:_____________________

Age:_______________

Height:________________________

Weight:___________________________

Avg miles run per week:_________________________

Any lower extremity injuries within the last 6 months?_______________________

Any cardiovascular or serious health issues?__________________

Females: Are you pregnant?_____________________ Result of pregnancy test:____________

Using the scale below, mark where your pain levels are during and/or after running.

No Pain ____ Worst Pain Possible

APPENDIX D

Retraining Session #1

Pain

No Pain ________________________________ Worst Possible Pain

Effort of Execution

Very Hard to Execute ________________________________ Very Easy to Execute

Naturalness

Very Unnatural ________________________________ Natural

Retraining Session #2

Pain

No Pain ——————————— Worst Possible Pain

Effort of Execution

Very Hard to Execute ——————————— Very Easy to Execute

Naturalness

Very Unnatural ——————————— Natural

Retraining Session #3

Pain

No Pain ________________________________ Worst Possible Pain

Effort of Execution

Very Hard to Execute ________________________________ Very Easy to Execute

Naturalness

Very Unnatural ________________________________ Natural

Retraining Session #4

Pain

No Pain ______________________ Worst Possible Pain

Effort of Execution

Very Hard to Execute ______________________ Very Easy to Execute

Naturalness

Very Unnatural ______________________ Natural

Retraining Session #5

Pain

No Pain ________________________________ Worst Possible Pain

Effort of Execution

Very Hard to Execute ________________________________ Very Easy to Execute

Naturalness

Very Unnatural ________________________________ Natural

Retraining Session #6

Pain

No Pain

Worst Possible Pain

Effort of Execution

Very Hard to Execute

Very Easy to Execute

Naturalness

Very Unnatural

Natural

Retraining Session #7

Pain

No Pain — Worst Possible Pain

Effort of Execution

Very Hard to Execute — Very Easy to Execute

Naturalness

Very Unnatural — Natural

Retraining Session #8

Pain

No Pain ________________________________ Worst Possible Pain

Effort of Execution

Very Hard to Execute ________________________________ Very Easy to Execute

Naturalness

Very Unnatural ________________________________ Natural

APPENDIX E

Follow-Up Data Sheet

Subject ID:_____________________

Avg miles run per week:_________________________

Did you experience any lower extremity pain or sustain any lower extremity injuries in the last 4 weeks?_______________________

Please specify: ____

Using the scale below, mark where your pain levels were during and/or after running over the past 4 weeks.

No Pain ____ Worst Pain Possible

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