# A 2-YEAR PROSPECTIVE COHORT STUDY OF ANTERIOR KNEE PAIN IN RUNNERS

BY

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## List of Abbreviations

Anterior Cruciate Ligament; ACL

Anterior Knee Pain; AKP

Anterior Superior Iliac Spine; ASIS

Body Mass Index; BMI

Body Weight; BW

Electromyography; EMG

Ground Reaction Forces; GRF

Iliotibial Band; IT Band

Iliotibial Band Stress Syndrome; ITSS

Magnetic Resonance Imaging; MRI

Medial Tibial Stress Syndrome; MTSS

National Institute of Health; NIH

Positive and Negative Affect Score; PANAS

Quadriceps Angle; Q-angle

Satisfaction with Life Scale; SWL

Screening Visit; SV

Short Form-12; SF-12

Standard Deviation; SD

State-Trait Anxiety Inventory Scale; STAI-S

The Runner's and Injury Longitudinal Study; TRAILS

Visual Analog Scale; VAS

## **Abstract**

Introduction: Running is a common form of exercise, but up to 79% of runners experience overuse injuries each year. Anterior knee pain (AKP) is the most common overuse injury in runners. The literature has equivocal results regarding risk factors for overuse injury and predicting injury.

Purpose: To compare runners who experience an AKP injury to runners that remain uninjured. These data could provide etiological evidence of AKP and could help clinicians treat and prevent AKP.

Methods: Runners in the TRAILS cohort (n=300) were followed in a prospective observational study for two years. The 101 uninjured runners were compared to the 58 runners that experienced AKP. Data collection occurred at baseline. Data included anthropometric, biomechanical, physiological, psychosocial, and training behavior measurements.

Results: Injured runners showed a decreased mental component of SF-12 scores and a greater knee stiffness at baseline. After a multivariable analysis, the mental component of SF-12 was predictive of AKP injury.

Conclusions: Runners who experienced AKP had lower perceived mental health scores than uninjured runners. Treatment and prevention of AKP should include a psychosocial component.

## Introduction

Running is a common form of exercise. In 2017, 65 million Americans reported being habitual runners[1]. There are health benefits associated with running. The Surgeon General has stated that regular physical activity can improve quality of life and reduce morbidity and mortality from common diseases[2]. Running acts as primary and secondary prevention of some of the most common chronic diseases including diabetes mellitus, osteoporosis, and cancer[3]. Unfortunately, many runners experience overuse injuries. The overall incidence of lower extremity running injury ranges from 19.4%-79.3% across various studies, with the most common injury site being the knee[4]. There are numerous potential treatments for running injuries including rest, cessation of running activity, orthotics, and surgery[5]. However, the exact etiology of running injuries is difficult to determine. Many studies cite increased mileage and previous injury as risk factors for running injury[6–8], but the exact physiologic or biomechanical risk factors are elusive.

Runners experience constant, repetitive collisions with the ground. While there are multiple theories as to why some runners experience overuse injuries, the data are relatively inconclusive. However, most would agree that inadequate rest time between exercise sessions can lead to overuse injury[9]. One study also found that runners with decreased impact forces and decreased loading rates tended to become injured less[10]. Some injuries seem to be more sex-specific, and others seem dependent on age[11]. Because the risk factors for overuse injury are so difficult to identify, our ability to identify those at risk of overuse injury is limited[12].

Psychosocial injury research is a relatively new topic regarding running injury. Having more stressors, certain personality characteristics, and fewer coping resources could lead runners to perceive a situation as stressful, causing a physiologic response that could lead to injury[13]. For example, a stressed runner may have more muscle activation and less relaxation, which could increase stiffness and lead to injury. Four distinct thought patterns appear common among injured runners: frustration due to the uncertainty of the injury and recovery process, fear relating to the injury and its potential inability to heal, the inability to meet personal goals, and the risk of becoming reinjured[14]. These psychological factors could lead to changes in runners' gait or the cessation of running altogether.

When examining running injuries, a multivariable approach is advantageous. Psychosocial, biomechanical, physiologic, training behavior, and injury history factors are all analyzed. It is believed that running injuries occur as a result of a combination of all of these factors, making it difficult to pinpoint the exact etiology[15].

There are various types of overuse running injuries including anterior knee pain, iliotibial band friction syndrome, Achilles tendinopathy, medial tibial stress syndrome, and plantar fasciitis. The predominant location of injury is the knee[4], and the most common injury type is anterior knee pain[16]. The purpose of this study is to compare biomechanical, physiological, and behavioral variables of runners who reported anterior knee pain during a two-year observational period to runners who did not report injury during the observational period.

## Review of Literature

Overuse injuries commonly experienced by runners are different from acute injuries. Overuse injuries occur from the accumulation of repetitive use and stress, whereas acute injuries are the result of a single traumatic event[17]. Additionally, overuse injuries can occur when the body is given inadequate time to heal between bouts of exercise[17]. Acute injuries have different pathologies than overuse injuries, and this study will focus on the latter in endurance runners.

### Epidemiology

Van Gent et al. found the incidence of lower extremity running injuries was between 19.4-79.3%[4]. The predominant location of injury was the knee with an incidence of 7.2-50.0%, followed by the lower leg with an incidence of 9.0-32.2%, the foot with an incidence of 5.7-39.3%, and the thigh with an incidence of 3.4-38.1%[4]. Of these injuries, 75% were due to overuse[8]. When examining specific populations of runners, the incidence rates are similar to the overall rate from van Gent et al. In a retrospective study of ultra-trail runners, 90% of the sample reported experiencing at least one running injury[18]. While the incidence rate is higher than the range above, the study had a small sample (n=40) and only assessed injury through self-report questionnaires. Interestingly, the ultra-trail runners reported injuries of the lower back more frequently than injuries of the knee. In a study of Australian military recruits, the incidence rate of injury due to running was 46.6% with 79.8% of those injuries occurring in the lower extremity[19]. In a 12-month study of soccer referees, the 31 participants reported 38 injuries over the year of observation. 61% of these injuries were overuse, and being injured during training or while refereeing a match had no effect on the proportion of overuse versus acute injury[20].

In a 12-week study of recreational runners, 27% experienced an overuse injury, with the lower leg and the knee being the most common injury sites[21]. Walter et al., in another study of recreational runners, found that 48% of runners were injured within 12-months after running a community road race, and that increased training mileage was the only significant risk factor[22].

Gender appears to have some influence on the incidence of injury. Taunton et al[23] examined runners in a 13-week training program and found a total injury rate of 29.5% across both genders. Some small injury site-specific gender differences appeared with men reporting injuries of the knee significantly more than women (36% versus 32%). Being female and less than 31 years of age was protective against injury [RR 95% CI, 0.575 (0.342, 0.967)] and being female and greater than 50 years of age was harmful [RR 95% CI, 1.919 (1.107, 3.328)]. Being female and training only one day per week was also harmful [RR 95% CI, 3.648 (1.082, 12.297)]. All other training frequencies were non-significant across both genders. In the primary outcome of this particular thesis's study, 73% of women were injured over a 2-year observational period whereas only 62% of men were injured[15]. However, the notion that female gender is a risk factor is still highly contested. Large studies like the Ontario Cohort Study[22] have found no gender differences, as did a meta-analysis by Saragiotto[24]. Despite this, Clement et al. suggested that all future running studies should be analyzed by genders[16].

## **Risk Factors**

Multiple factors are associated with the risk of running overuse injuries. Unfortunately, there is no consensus as to which risk factors are most important to study. This has led to a vague picture of what causes injury[8]. Despite this, several variables are consistently associated with overuse injuries. The most commonly assessed variables include anatomical structures, demographics, and training behaviors.

Messier et al[25] proposed a theoretical framework combining weekly mileage and risk factors. For those with higher risk factors, the threshold of injury occurs at a lower weekly mileage than those with fewer risk factors. However, even those runners with few risk factors can reach an injury threshold if they run enough miles per week. Overuse injury is an interplay between all of these factors.

***Q-Angle***

The quadriceps angle, or Q-angle, is the angle formed by the intersection of two lines, one from the anterior superior iliac spine (ASIS) to the center of the patella and one from the tibial tuberosity to the center of the patella[26]. It measures the alignment of the quadriceps muscles with the skeletal system underneath, namely the pelvis, tibia, and femur[27]. Q-angle is often used as a derivative measure of lower limb alignment[28]. Large q-angles are associated with hip adduction and femoral internal rotations, and it is thought that this can lead to a diagnosis of anterior knee pain[29]. However, when examining the data across multiple studies in a review of q-angle, Caylor et al. found the results to be equivocal[30]. Messier et al. found that the q-angles in runners with patellofemoral pain were larger than in runners without[25]. Huberti and Hayes found that increased patellofemoral contact pressures occurs in cadavers with q-angles above and below normal (<8°, >17°)[31]. Compared to unaffected high school athletes, Moss et al. found greater q-angles in those who reported patellofemoral stress syndrome[32]. The results appear to be equivocal because there is no universal method of measuring q-angle[30]. Some studies measure the participant while supine and some while standing.

Some have the knee extended and some have the knee flexed. Until a universal method is implemented, the results will be difficult to interpret.

### *Height and Age*

Height and age seem to have some effect on the risk of overuse injury in runners. Taunton et al. found that female runners over 50 years of age were at increased risk of overuse injury when compared to similar aged male runners[23]. The Ontario Cohort study found that increased height increased the injury risk for males but not females[22].

### *Pes Cavus*

High arched feet, or pes cavus, has consistent etiologic evidence linked to overuse injury in runners. The foot as an organ is used to distribute force, absorb shock, balance, and propel. In a normal gait cycle, the foot will pronate at heel strike to distribute forces and lessen the stress on any one particular joint. At toe-off, the foot supinates and becomes rigid to provide a base from which to propel forward[33]. In pes cavus feet, the rearfoot remains underpronated throughout the gait cycle, limiting the foot's flexibility and ability to pronate to absorb and distribute shock[34]. Multiple studies have linked pes cavus feet to overuse injuries[25,35–37]. Pes cavus runners generally experience greater leg stiffness, although no increased knee stiffness[38].

### *Stiffness*

Stiffness is the slope of the stress-strain relationship. Clinically, it is the decreased ability of a joint to attenuate the force during stance. Having stiff joints could be a risk factor for overuse injury, as stiff joints would experience greater forces than less rigid joints. Scott and Winter[39] showed that joints experience large forces during running, usually between 3-4 times body weight at the knee. More stiff joints would experience even greater forces. Specifically, Williams et al. found a total leg stiffness of 7.17±1.16 kN/m kg in runners with cavus feet compared to a stiffness of 6.46±1.01 kN/m kg in runners with planus feet, as well as increased loading rates in high-arched runners than in low-arched runners[38]. There are, however, limited studies examining the relationship between joint forces and joint stiffness.

***Rearfoot Motion***

Another factor associated with running injuries is excessive pronation of the subtalar joint. The lower limb is often discussed as a closed kinetic chain, but the foot and ankle independently can also be considered a closed chain[40]. In a closed chain, the terminal joint (the foot) experiences the most force. Forces are then distributed and attenuated as they go up the chain. Subtalar pronation and supination are triplanar movements; pronation consists of abduction, dorsiflexion, and eversion, and supination consists of adduction, plantar flexion, and inversion[41]. These complex motions help attenuate the forces as they rise up through the limb. As the foot strikes the ground during running, pronation helps to distribute and attenuate forces. As the foot prepares to toe-off, it supinates to become rigid and provide a stronger base from which to propel. Not only do excessive pronators experience increased torque and stress on the joints of the foot and ankle[25,42], they also are less able to supinate upon toe-off[42]. Maximum eversion in normal pronators is 11.2±2.7°, whereas excessive pronators have a maximum eversion of 21.2±4.8°[43]. However, Messier et al. found that maximum eversion between injured and uninjured runners was relatively the same at 13.4±3.6° and 13.8±3.7°, respectively (p=0.35)[15]. Hence, data examining the relationship between excessive pronation and overuse injury is equivocal.

The velocity of the joints as they move through their ranges of motion has also been examined as a risk factor for overuse injury. Interestingly, Dorsey et al. found that runners with high arches, a factor generally considered to increase one's risk of injury, had lower eversion velocities than those with low arches (165.96±58.23 deg/s vs. 219.30±65.34)[44]. Though not significant, Messier et al.[25] found differences in pronation velocity between injured and non-injured runners. Injured runners had lower pronation velocity in the more commonly injured foot (right side), but higher pronation velocity in the less commonly injured foot (left side). These data are difficult to interpret, but rearfoot motion is still examined in most studies to date.

### *Previous Injury*

Across most studies, previous injury seems to be the greatest risk factor for developing an overuse running injury. The Ontario cohort study[22] showed that previously injured men were 1.69 (95% CI, 1.27-2.25) times more likely to be injured than their uninjured counterparts, and injured women were 2.35 (95% CI, 1.33-4.07) times more likely to be injured than their respective uninjured counterparts. The Vancouver Sun Run study[23] found that about half of injured runners reported a previous injury. Maughan and Miller[45] found that 24% of injured marathon runners experienced a previous injury. While we know that previous injury is a significant risk factor, just like running injuries in general, the exact etiology remains unclear. It is important to note, however, that until a runner returns to their original running mileage, they are not considered "recovered," and are still injured[46]. Not all studies that look at previous injury utilize this method, and therefore, not all correlations with previous injury are the same.

Just like previous injury, a runner's weekly mileage seems to be associated with their prospective risk of injury, but the data is mixed. In the Ontario cohort, Walter et al.[22] found that running more than 40 miles per week increased one's risk of overuse injury by 2.2 (95% CI, 1.30-3.68) times in men and 3.42 (95% CI, 1.42-7.85) times in women compared to runners who run less than 10 miles per week. This could be because increased times spent running increases your exposure to other risk factors, but the association still exists. Conversely, Messier and Pittala[47] found no significant difference in injury between those who train at different mileages. In another study, Messier et al.[25] found that injured runners ran significantly *less* than non-injured runners (20.94±1.60 miles per week versus 30.30±2.68). Related to the mileage ran, the frequency of running also seems to influence overuse injury. Walter et al[22] found that men who run throughout the entire year are 1.64 (95% CI, 1.12-2.35) times more likely to experience injury than men who do not run year-round, and women who run throughout the entire year are 2.00 (95% CI, 1.01-3.75) times more likely to experience injury than women who do not run year-round. Perhaps more relevant, the same study found that women who train 7 days per week were 5.50 (95% CI, 1.44-17.39) times more likely to be injured than women who run 0-2 days per week. Other frequencies in women were non-significant. The number of days running per week in men showed a dose-response relationship; as men run for more than 2 days per week, their risk of injury significantly increases up to 5.92 (95% CI, 2.49-12.75) times more for men who run 7 days a week than men who run 0-2 days per week. Again, this could be because increased frequency of running increases one's exposure to other risk factors, but it could also be attributed to the lack of time needed to recover after a run. Repeated exercise without rest in between is one proposed mechanism of overuse injury.

***Running Pace***

Running pace has also been proposed as a risk factor for overuse injury, again with mixed results. The Ontario cohort study[22] found that male competitive runners are 1.73 (95% CI, 1.21-2.49) times more likely to experience injury than fitness runners. The result for female competitive runners was non-significant, although it trended towards injury [1.93 (95% CI 0.97-3.89)]. Messier and Pittala[47] found no significance between different training paces and injury. In another study, Messier et al.[25] again found no significant difference in training pace between injured and non-injured runners. One study found that the effect of running pace greatly decreased when adjusting for weekly mileage[6]. Many studies note that the self-report nature of running pace is a limiting factor towards the data. The pace reported may not be exact, so it is difficult to draw conclusions from the data presented.

***Kinetics***

Kinetic forces are perhaps the most conspicuous risk factor in the literature. The joints of the lower extremity experience tremendous force while running. Scott and Winter[39] found that the compressive forces in the ankle peaked at 11.2 BW during running, and the Achilles tendon force peaked at 6.3 BW. The patellar tendon force peaked at 5.7 BW during running. When these high forces are unevenly distributed across a runner’s anatomy, injury can result in the soft tissue. The main proposed kinetic factors are: ground reaction force magnitude, joint moments, and loading rate[10,25]. Novacheck[48] found that ground reaction forces are actually not higher when running, but they must be absorbed in 1/3 of the time when compared to walking. Messier et al.[25] found that runners with patellofemoral pain had greater vertical propulsive forces in the uninjured leg, perhaps to compensate for the injured leg. They also found that the injured leg had less anteroposterior braking force when compared to the control group, likely because they were running at slower speeds to compensate for the running injury. However, Crossley et al.[49] found no difference in ground reaction force between runners with tibial stress fractures and uninjured runners. Another study[10] found that injured runners had a greater vertical force impact peak than uninjured runners, providing similar results to Messier et al.

Impact forces at heel strike are not the only factors that determine peak internal forces. Scott and Winter[39] noted that the internal force is dependent on not only the ground reaction force, but also the dominant active muscles. Muscle forces are needed to control knee flexion and to provide a base for push-off. Multiple factors affect the internal forces, but the authors did note that ankle plantarflexors provided anti-shear mechanisms to attenuate the force experienced at the ankle. Messier et al[12] found that decreased hamstring flexibility actually increased knee moments, and that body weight was significantly correlated with patellofemoral and tibiofemoral compressive forces.

Internal forces are greater at common injury sites[39], and greater internal forces are thought to be related to overuse injury. Kinetic data from multiple studies show that outside factors such as flexibility and body weight can alter the internal forces regardless of the initial ground reaction force[39]. All of these factors are interrelated. As said before of multiple risk factors, it is difficult to identify an individual risk factor's effect on injury; they must all be looked at collectively.

### *Psychosocial Factors*

Relatively new in the literature of chronic injury, psychosocial factors also play a role in overuse running injuries. Runners are psychologically affected during injury, during recovery, and even after the injury has healed. In a study of elite collegiate athletes, Shuer and Dietrich[50] used the Impact of Event Scale to compare the psychological response to injury to other known psychological events. There are two subscales: intrusion and avoidance. Intrusion measures unwanted thoughts or feelings, and Avoidance measures denial and emotional avoidance. On the intrusion scale, runners with chronic injury scored similar to those who have experienced a natural disaster. However, runners with chronic injury scored higher on the avoidance scale, showing that they were in denial more than their counterparts. Female avoidance scores were higher than their male counterparts, but there was no difference in the intrusion scale. These data show that even athletes struggling with minor chronic injury should be given adequate care and attention both physically and emotionally.

In a descriptive study of overuse injuries in long-distance runners, Russell et al.[14] found that there were four sub-themes of psychosocial distress across the injury timeline: frustration, fear, general distress, and social influence. Injured runners were often afraid of hurting themselves again and were frustrated that they were still hurting when they returned to running. They did, however, report having several friends and family to discuss their injuries with, but still experienced general overall distress. Most runners attributed their injuries to overuse or improper training, and most were hesitant to seek medical care, preferring instead to “run through the injury.” Russell et al. propose that this puts them at increased risk of future injury[14]. Most of the runners reported that they learned lessons from their injury, namely that overtraining probably led to their injury in the first place and how to change their training behaviors to avoid future injury.

In a study comparing runners with acute and chronic injuries, Wasley and Lox[51] used the Rosenberg Self-esteem Inventory to quantify psychosocial responses to injury. While there was no difference in the Accepting Responsibility subscore between the groups, runners with chronic injury scored higher on Avoidance (2.4 ±1.2 vs. 1.9 ±0.6) and lower on Seeking Social Support (2.5 ± 0.6 vs. 2.8 ± 0.4) than their acutely injured counterparts. Furthermore, chronically injured runners scored more negatively on self esteem (6.2 ± 1.2 vs. 4.4 ± 1.2) than acutely injured runners. These data suggest that runners with chronic injury respond differently to injury and cope differently than acutely injured runners.

While it appears that runners are subject to psychosocial influences in regards to injury, more work must be done to confirm and define the relationship. Most studies focus on athletes in general and not runners specifically. Future research should include more standard measurements on consistent populations.

## Running Injuries

The most common overuse injuries related to running are medial tibial stress syndrome (MTSS), Achilles tendinopathy, plantar fasciitis, patellar tendinopathy, iliotibial band stress syndrome (ITSS), tibial stress fractures, and anterior knee pain (AKP)[52].

### *Medial Tibial Stress Syndrome (MTSS)*

MTSS, more commonly known as 'shin splints,' is characterized by exercise-induced pain on the posteromedial side of the mid- to distal tibia[53]. The overall incidence of MTSS ranges from 4-35% of runners, with both extremes coming from military studies[53]. A systematic review of MTSS defined the syndrome as including: (1) pain along the posteromedial border of the tibia, (2) diffuse pain, and (3) pain that is activity related[54]. The same review found the pooled risk factors of MTSS to be female sex, higher weight, higher navicular drop, previous running injury, and greater hip external rotation with the hip flexed. One study[55] of forty-two runners found that those who reported MTSS demonstrated higher tibia varus angles, reduced static dorsiflexion, and longer duration of eversion. Interestingly, there was no difference in eversion velocity between the injured and uninjured groups. Another study of naval recruits[56] found that those who experienced MTSS were more likely to be female and had a more "pronated foot type." While there does not appear to be an exact consensus on the risk factors, it seems that female sex and greater pronation are fairly consisted across the literature.

It was once believed that MTSS was due solely to referred pain from the tibialis posterior muscle[57]. However, in a cadaver study done in 1994, Beck and Osternig[58] found that it is actually the soleus and not the tibialis posterior that originates in the tibia at the location of MTSS pain. Kortebein et al.[57] noted that the flexor digitorum longus also originates near the site in many persons with MTSS. Based on these data, it is now commonly accepted that MTSS is due to referred pain from the soleus muscle and potentially from the flexor digitorum longus. Kortebein et al. also proposed that MTSS may be due to a dysfunction of the Sharpey fibers, a network of fibers that connect the soleus fascia to the tibia.

Even though there is no true consensus on the anatomical origin of MTSS, most would agree that it involves some form of fatigue or dysfunction of the soleus. Beck[59] proposed that increased ground reaction forces over time could fatigue the soleus to the point of injury. Similarly, Madeley et al.[60] found that runners with MTSS had decreased endurance of the ankle plantar flexors after an adjustment for age, height, and BMI, showing that fatigue may be related. Even though there is no consensus on etiology, the treatment for MTSS is consistent. Most would recommend some combination of rest, cryotherapy, cross-training, orthotics, and a slow return to normal activity levels[57].

***Achilles Tendinopathy***

The Achilles tendon is the thickest, strongest tendon in the body[61]. It is formed from interweaving tendons from the gastrocnemius and soleus muscles. Achilles tendinopathy is a common overuse injury seen in runners representing 5-18% of all running-related injuries[62]. It is multifactorial due to a combination of biomechanical, anatomic, and training variables[61]. There is very little blood flow to the Achilles tendon, almost priming it for injury[63]. The main characteristics of Achilles tendinopathy are pain, swelling, decreased ankle range of motion, stiffness, and , in advanced cases, a nodular appearance of the lower leg and ankle[64].

The most widely accepted mechanism of injury relates to the pronation and supination of the foot during heel strike and toe off. At every heel strike, the foot pronates, followed by a rapid supination to prepare for toe off. This constant back-and-forth motion causes the Achilles tendon to whip back and forth almost like a bowstring. This repeated motion wears the tendon out over time[64]. Furthermore, if the runner excessively pronates and remains pronated at the start of knee extension, the lateral rotation of the tibia at the knee combined with the medial rotation of the tibia at the pronated ankle cause a twisting motion at the tendon[64]. Both of these motions can affect the tendon over time.

Overpronation appears to be a compensatory mechanism for multiple anatomic abnormalities including cavus foot and varus alignment of the lower extremity[64]. Since over-pronation aggravates Achilles tendinopathy, these anatomic abnormalities are widely accepted as risk factors for Achilles tendinopathy. Treatment options vary, but include eccentric musculotendinous training, corticosteroid injections, night splints, biomechanical evaluations, and surgical treatment, including tenotomy and removal of tendon pathology[65].

***Plantar Fasciitis***

Plantar fasciitis is caused by inflammation of the plantar fascia, the thick connective tissue that connects the heel to the toe. According to Chandler and Kibler, 10% of runners will experience plantar fasciitis[66]. Furthermore, 20-30% of cases will be bilateral[67]. The plantar fascia is responsible for maintaining the arch of the foot, and can become inflamed following repeated stress or tears[68]. There are three parts to the plantar fascia: medial, central, and lateral. The central portion is believed to be most related to supporting the arches of the foot.

The plantar fascia prevents foot collapse by its tensile strength[69]. Basically, the fascia serves to resist downward forces from gravity and upward ground reaction forces that would otherwise flatten out the foot. Furthermore, the fascia is involved in what is known as the Windlass mechanism. As the hallux dorsiflexes during gait, the plantar fascia, which connects the calcaneus to the metatarsophalangeal joint, tightens and maintains the medial arch of the foot[69].

The most widely accepted risk factors in the literature for plantar fasciitis are pes cavus feet and excessive pronation. It makes sense that pes cavus, or high-arched, feet would be a risk factor for plantar fasciitis, because a high arched foot should experience greater tension of the fascia, which should result in more pain and stretching[70]. As the plantar fascia stretches and becomes inflamed, it can lead to the formation of a bone spur on the calcaneus. Bolgla and Malone proposed that the bone spur is another likely mechanism of the continues pain seen in those with plantar fasciitis[69]. In the same study, they also found that excessive pronation decreases the efficacy of the Windlass mechanism. Messier and Pittala[47] found that runners with plantar fasciitis had reduced plantar flexion when compared to uninjured runners. Pohl et al.[71] found that runners with plantar fasciitis had increased dorsiflexion of the foot. Anatomy and motion of the foot both seem to influence the development of plantar fasciitis.

***Iliotibial Band Stress Syndrome (ITSS)***

The iliotibial (IT) band is a large band of fascia that runs along the lateral side of the thigh. It crosses both the hip and the knee and stabilizes the knee as it flexes and extends. It also allows various motions of the thigh, including abduction, adduction, and rotation. The IT band encloses the tensor fascia latae and attaches together the gluteus maximus and gluteus minimus as they insert into the thigh and knee[72]. The most common symptom of ITSS is pain at the lateral knee secondary to inflammation of the IT band at its distal portion[73]. ITSS is caused by excessive friction as the IT band slides over the lateral femoral epicondyle during repetitive flexion and extension of the knee[73]. Specifically, the IT band passes over the epicondyle during full knee extension. MRI imaging of the lower limb of runners with ITSS show that the lower portion of the IT band is thickened, and the potential space underneath the band becomes filled with fluid[74]. Thickness of the band in the injured group was 5.49 ± 2.12 mm compared to 2.52 ± 1.56 mm in the uninjured group. The same study found that runners with slower running paces and less knee flexion (<30°) were more inclined to develop ITSS. This is likely because the decreased flexion means that the knee is more extended throughout gait, and therefore rubs over the epicondyle more, causing increased friction and inflammation.

Muscle weakness and joint motion appear to be related to ITSS. Noehren et al.[75] found that female runners with ITSS had greater hip adduction and knee internal rotation but, contrary to the assumptions above, no difference in knee flexion. In a similar study with men, Noehren et al.[76] found that men with ITSS had weaker hip external rotators, greater hip internal rotation, and greater knee adduction than their uninjured counterparts. These data indicate that neuromuscular control of the hip and knee should be targeted when preventing and treating ITSS.

***Anterior Knee Pain (AKP)***

AKP is the most common overuse running injury[15]. Annual prevalence of AKP in the general population was 22.7% in 2018, with females reporting AKP more than males (29.2% vs. 15.5%)[77]. In elite athletes, the prevalence can be even higher. The same study found that elite cyclist had a prevalence of 35.7%.

The normal knee is composed of bones, ligaments, tendons, and cartilage. All of the structures together make movement easy. Changes in anatomy or changes in biomechanics, however, can alter the functionality of the knee and cause pain. One important biomechanical change that affects AKP is patellar tracking. The patella normally sits in the trochlear groove, and easily slides up and down as the quadriceps contract and relax. In many persons with AKP, the patella tracks to the side of the groove. Draper et al.[78] used real-time MRI to show that patients with PPS have increased lateralization and lateral tilt of the patella during squatting motions. Witvrouw et al.[79] showed that those with a hypermobile patella had a high correlation with AKP.

A highly mobile patella could be due to muscle weakness around the knee joint. Cowan et al.[80], using electromyography, found that the vastus medialis was slower to activate than the vastus lateralis in those with AKP, which could cause lateral tracking of the patella. In a systematic review of AKP, Waryasz and McDermott[81] found that decreased hamstrings and quadriceps strength were both correlated with anterior knee pain. The same review also found that IT band tightness was positively correlated with AKP, showing that some of these overuse injuries can be related.

Q-angle, while having mixed results, appear to be associated with AKP. Messier et al.[25] found that Q-angles greater than 16° were associated with injury. However, Almeida et al.[82] found no correlation between Q-angle and severity of knee pain. It would seem that malalignment along with muscular weakness together constitute more risk than either alone.

## **Knee Model**

There are two methods to quantify joint forces: forward and inverse dynamics. Forward dynamics involves the calculation of movements and external reaction forces from known internal forces or moments. Inverse dynamics is the exact opposite and involves the calculation of internal forces or moments form known external movements or forces[83]. Forward dynamics uses electromyography (EMG) to calculate internal forces and then uses those values to predict ground reaction forces. However, inverse dynamics would still be required to verify the values for ground reaction forces. Most models include both forward and inverse dynamics.

The Messier research group has utilized a biomechanical knee modeled that was first implemented by DeVita and Hortobagyi. Both Messier and DeVita detail the exact method in their papers[84,85]. Essentially, inverse dynamics were used to calculate lower extremity joint forces and moments, and, together with collected kinematic data, the forces of the three largest knee muscles and the force of the lateral collateral ligament were calculated. These calculated forces were then combined with the joint reaction forces of the knee to find the tibio-femoral compressive and shear forces. The model allows for the calculation of gastrocnemius and hamstring forces as well form the extensor moment of the hip that can be observed during the first half of stance[85].

There are a few limitations to the DeVita model. It does not calculate the forces of cruciate and medial collateral ligaments, and therefore increases the knee muscle force predictions. The effect is likely quite low because all of the forces are produced by the sum of every structure in the knee. Another major limitation is that the model assumes there is no co-contraction of muscles during the stance phase, specifically the hip flexors and the hip abductors. Assuming no co-contraction reduces the predicted effect of the rectus femoris, which in turn would affect the knee and gluteus medius forces. The EMG activation of these muscles during the first half of stance when the co-contraction would be most present is actually fairly low, so the effect should be minimal. A third limitation is that the model cannot accurately predict the contribution of smaller muscles and ligaments. Recent studies suggest that in patients with knee osteoarthritis specifically, the vastus lateralis and vastus medialis are activated at different levels as a compensatory mechanism[86]. The DeVita model has difficulty differentiating between the different muscles of the quadriceps, as well as the smaller anatomical structures of the knee.

## Limitations in the Literature

Research on running overuse injuries has yielded many equivocal data. Additionally, there is no standard set of variables between research groups. Furthermore, the measurement of some variables differs from group to group. For example, q-angle is measured in a supine position by some researches and a standing position by other researchers. All of these factors lead to a vague picture of what causes overuse running injuries.

## Rationale and Purpose

Currently, the literature on overuse running injuries includes a combination of retrospective studies, studies on athletes that are runners secondarily, or expert opinions. There are very few prospective studies on overuse running injuries. Furthermore, the studies to date do not use a standard set of variables which leads to a vague picture of the true causes of overuse running injuries. Despite these limitations, the literature has determined that anterior knee pain (AKP) is the most common running overuse injury. Therefore, the purpose of this study is to compare runners who sustain an AKP injury to runners that remain injury free. We will compare biomechanical, behavioral, physiological, and psychological risk factors to provide high-quality evidence of the etiology of AKP in the hopes of improving the clinical treatment and prevention of AKP.

## Methods

### *Study Design*

The Runner's and Injury Longitudinal Study (TRAILS) was a prospective observational study conducted over 18 months. This arm of the study compared the baseline data of runners who were diagnosed with anterior knee pain to the baseline data of runners that remained uninjured.

### *Study Timeline*

Participants who successfully completed an eligibility questionnaire during the pre-screening visit (generally a phone call) were enrolled into the TRAILS cohort. Baseline measurements were collected over two screening visits. Baseline measurements included biomechanical, behavioral, physiological, and psychosocial variables. A complete diagram of the study can be seen below.

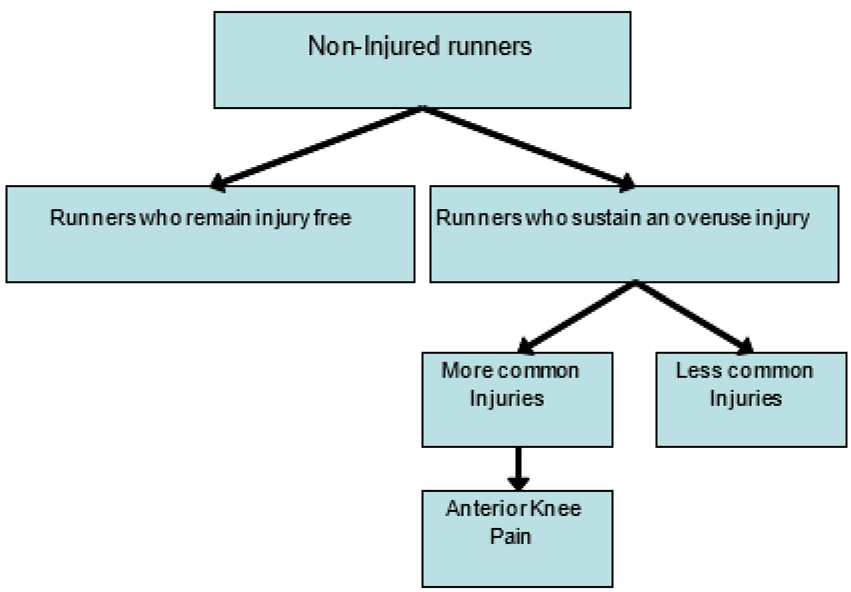


Figure 1: Study Diagram

### *Screening Visit 1 and 2*

After eligibility was confirmed during the pre-screening visit, participants came to Wake Forest University for screening visits 1 and 2. At screening visit 1, voluntary informed consent was obtained by study staff. Following consent, study staff obtained the participants' medical history, running and injury history, demographics, medications, and anthropometric measurements. Study staff also obtained isokinetic strength data of the knee and ankle using an isokinetic dynamometer.

On a separate date usually two to four weeks after screening visit 1, participants again came to Wake Forest University for screening visit 2. At this visit, data for a 3-dimensional gait analysis were obtained as well as psychosocial well-being data and isokinetic hip strength.

### *Follow-up Visits*

Participants were brought back at 6 and 12 months and subsequent to any running-related injuries.

### *6-month Follow-up*

6 months into the study, participants were brought back for another visit. Questionnaires regarding medications, training history, and psychosocial measurements were repeated.

### *12-month Follow-up*

Similar to the 6-month follow-up, this visit again included repeat measurements of medications, training history, and psychosocial variables. In addition, participants were given an incentive of a $100 gift certificate towards a new pair of running shoes from a local shoe store.

### *Follow-up Injury Visit*

This visit could occur at any time but only after a participant reported a running-related injury. Running injuries were classified using a method from Marti et al.[6] Injuries were classified as either Grade I, II, or III. Those with a Grade I injury continued training despite symptoms. Those with a Grade II injury decreased weekly mileage. Those with a Grade III injury had their training interrupted for at least two weeks. For this study, anterior knee pain of all three grades were included. Participants were emailed biweekly during the study to assess training behaviors and to inquire about any injuries. Participants who reported a running-related injury were scheduled an appointment to meet with the study physician. All costs were covered by the study. After meeting with the physician, participants were offered one free physical therapy evaluation if deemed appropriate by the study physician. Injured runners were then enrolled into the Injury Recovery Protocol, which covers a different aim of the overall study. Runners were given an additional $100 gift card for attending the Injury Recovery visit.

After the visit with the physician, injured runners were emailed weekly to assess their injury status. Runners were deemed "recovered" after returning to full pre-injury mileage. Once full mileage was achieved, injured runners were again assessed over two Injury Recovery Visits for a supplemental study. The first visit retested medications, flexibility, training history, and 3-D gait analysis. The second visit retested isokinetic strength and psychosocial well-being measurements.

### *Participants*

Study staff recruited both male and female runners from the Winston-Salem community on a rolling basis. Recruitment focused on a multimedia approach with advertisements distributed online, in local running clubs, newspapers, and running journals. Further details can be seen here[15].

Participants were included if they met the following criteria: injury-free for 6 months, willing to participate in a one year study, average weekly running mileage greater than 5 miles per week for the previous 6 months, age 18-60 years old, living within 200 miles round-trip of Winston-Salem, and not planning on leaving the area for two years.

Participants were excluded if the met the following criteria: had a diagnosed chronic musculoskeletal disease (arthritis, osteoporosis, multiple sclerosis), coronary disease, orthopedic condition (ACL tears, joint replacement, joint surgery), pregnant, unwilling to attend testing sessions, or showed no interest.

## Data

A diagram of which data were collected at which visit is displayed below. Psychosocial characteristics were collected at baseline (not shown in diagram).

| Measurements | PSV | SV1 | SV2 | $FU_{injury}^{+}$ | FU6 | FU12 |
|---|---|---|---|---|---|---|
| **Eligibility and Descriptive Measurements** | | | | | | |
| Eligibility Questionnaire | Xc | | | | | |
| Medical History | | X | | | | |
| Informed Consent | | X | | | | |
| Demographics | | X | | | | |
| Medication Use | | X | | X | | X |
| **Injury Measurements** | | | | | | |
| Physician Injury Evaluation | | | | X | | |
| Injury Status (Phone Call) | | | | X | X | X |
| MRI/X-ray (as necessary, to confirm diagnosis of anterior knee pain.) | | | | X | | |
| **Primary and Secondary Outcomes** | **PSV** | **SV1** | **SV2** | **$FU_{injury}^{+}$** | **FU6** | **FU12** |
| Biomechanical Factors | | | | | | |
| Rearfoot Biomechanics | | | X | | | |
| Knee Joint Loads | | | X | | | |
| Behavioral Factors | | | | | | |
| Runner's Training History | | X | | X | X | X |
| Injury History | | X | | X | X | X |
| Physiological Factors | | | | | | |
| Strength (Knee, Ankle) | | X | | | | |
| Strength (Hip) | | | X | | | |
| Anthropometrics | | X | | | | |

Figure 2: Data Collection

### *Anthropometric Measures*

Flexibility of the lower extremity and Q-angle were measured using digital photographs with a method from Herrington and Nester[87]. A Nikon Coolpix L22 12.0 Megapixel digital camera was used to capture images that were then uploaded to NIH ImageJ software to process data. Anatomical markers were placed on the participants on identifiable bone structures for measurements. One picture was taken for Q-angle, and three pictures were taken for flexibility measures of the quadriceps, hamstrings, plantar flexors, and dorsiflexors on each side of the participant. Flexibility of the lower extremity was measured as an average of the three data collected at each location.

Markers were places on the greater trochanter, lateral condyle of the femur, lateral malleolus, and 5th metatarsal. Quadriceps flexibility was measured as the angle formed between the greater trochanter, latera condyle, and lateral malleolus at maximal knee flexion in the absence of hip flexion. Participants were asked to lie in a prone position with their thighs strapped down to minimize hip flexion. They were then asked to manually flex the knee on one side at a time and hold the position until a photograph was taken. This was repeated three times on each side. Hamstrings flexibility was measured with the same markers but with the participant in a supine position with the non-measured leg strapped down and the measured leg in 90° of hip flexion. Participants were asked to extend the knee and hold until a photograph was taken. This was repeated three times on each side.

For ankle flexibility (plantar flexion and dorsiflexion), angles were measured using the lateral condyle, lateral malleolus, and 5th metatarsal. The ankle was first placed into a box to ensure a neutral angle of 90°. The box was then removed, and the participant was asked to maximally plantar flex the foot until a photograph was taken. The participant was then asked to maximally dorsiflex the foot until a photograph was taken. This was repeated three times on each side to obtain all necessary photographs.

Q-angle was measured with the participant standing on a standardized template with markers placed on the anterior superior iliac spine (ASIS), center of the patella, and tibial tuberosity. A photograph was taken with the participant standing still. The Q-angle was measured as the acute angle formed from the intersection of a line drawn from the ASIS to the center of the patella and the tibial tuberosity to the center of the patella.

Instead of arch height, a surrogate measure known as arch index was used. Details of the measurement can be found here[88]. A footprint was obtained by having participants apply no greater than 50% of their body weight on one foot on an ink-marked pad. A footprint was obtained from both sides. Arch index was calculated as the area of the middle third of the ink-marked foot over the entire area of the ink-marked foot, excluding the phalanges.

***Physiologic Measures***

Muscular strength was measured using a Kin-Com 125E isokinetic dynamometer or a Humac Norm isokinetic dynamometer for later participants. A pilot study using 8 participants was used to compare the two dynamometers, and a fixed-effect model of regression analysis showed no statistical difference. Further details on the pilot study can be found here[15]. Maximal concentric and eccentric values were obtained at the knee and ankle during SV1, and maximal isometric and concentric values were obtained at the hip during SV2. Right and left legs were alternated for each participant to limit the effects of fatigue or practice. The first joint evaluated (knee or ankle) was also alternated for each successive participant. Two maximal reproducible trials were averaged with no more than 6 trials per testing condition. Prior to testing each joint, the participants warmed up at 50% of their maximal voluntary contraction to habituate participants to the equipment. For each maximal effort, consistent verbal encouragement from the test administrator was provided. Torque (Nm) was converted to force (N) by dividing the torque by the participants limb length.

Knee flexion and extension strength was measured at an angular velocity of 60°/second. The order for all participants was knee extension (concentric and eccentric at 60°/sec) followed by knee flexion (concentric and eccentric at 60°/sec). Participants were fastened to the testing chair using waist and shoulder straps. Hands were placed across the chest, and the dynamometer axis was aligned with the knee. Resistance pads were attached to the lower limb proximal to the ankle joint. Gravity-effect torque was calculated using the weight of the leg at 45°. Activation force was set to 50% maximal voluntary contraction as measured previously. Knee extensors were tested through a joint arc of 90° to 30° (with 0° representing full extension). The first and last 10° were cut out to account for acceleration and deceleration of the equipment, so knee extensor strength was measured as an average from 40-80° based on two maximal reproducible trials separated by 30-60 seconds of rest. Knee flexion and extension strength was measured using the same protocols and same degrees of motion.

Ankle plantar flexion and dorsiflexion were measured similar to the knee joint. The foot was fastened with the pivot point of the ankle aligned with the dynamometer. 15° of plantar flexion was measured followed by 15° of dorsiflexion. 60 seconds of rest was given between each trial. The first and last 5° was removed from analysis to account for acceleration and deceleration of the dynamometer. An angular velocity of 60°/second was again used.

Hip isometric strength was measured at a separate visit since the protocol differs slightly. Hip isometric strength was measured for 3 seconds at 0° of hip abduction. Activation force was set to 50% maximum voluntary contraction, and hip abductors were measured through a joint arc of 0-30°. The first and last 5° were removed to account for acceleration and deceleration of the dynamometer, so hip average force was calculated from 5-25° of hip abduction. Two maximal reproducible trials were averaged with no more than 6 trials performed and 30-60 seconds of rest in between trials.

***Gait Analysis***

Lower extremity mechanics were analyzed using both kinetic and kinematic data. Kinematic data were captured using a 6-camera motion capture system. The cameras collected data at 200Hz and were synchronized with two strain-gauge force plates that captured kinetic data at 480Hz. Participants were asked to run their normal training pace down a 22.5m runway while the cameras captured their motion. Running pace was confirmed using Lafayette Model 63501 photoelectric control system that utilized digital timekeeping with sensors placed 4m apart. A trial was considered successful if the running pace was within 3.5% of the reported running pace, the full foot struck the force plate, and the runner did not target the force plate. An average of three successful trials was used for each leg. Following the Cleveland Clinic configuration, 33 reflective markers were paced at anatomical landmarks on each participant for motion capture. 15 separate markers were placed on the rear foot and the shank for rearfoot motion analysis. By combining the force plate data with the motion capture data, kinetic and kinematic data were collected simultaneously for each participant.

Kinetic data were collected using two strain-gauge force plates that measured vertical and anteroposterior ground reaction forces. Using the DeVita biomechanical knee model[84], specific knee forces were calculated. That model is described below.

Kinematic data were collected and processed using Cortex 7.0 Motion Analysis software. Once processed, collections were transferred to Visual 3-D to compile kinetic and kinematic data. Data were then transferred to Quick Basic so they would be in formats that were easily transferrable between systems.

A lab technician checked and edited all motion capture data. Using Cortex 7.0 software, the technician first confirmed that all captured markers were labeled correctly. In the case that markers were not captured, the technician calculated and placed virtual markers in the data using either cubic join or virtual joint equations. Inverse dynamics were then applied using the DeVita model to calculate joint forces and moments at the knee, hip, and ankle.

***Biomechanical Knee Measures***

The DeVita model calculates forces in the tibiofemoral compartment of the knee. External joint torques are used to calculate individual muscle and ligament forces. The model has two main parts. First, a 3-D gait analysis collects kinematic and kinetic data that allows for inverse dynamics calculations of the joint forces and moments at the ankle, knee, and hip. Second, kinematic and anatomic data are combined with the joint force data to calculate individual muscle and ligament forces. All of these data allow for the calculation of maximal knee compressive forces.

For the first part, the lower extremity was marked as a rigid, linked system. Magnitude of the segmental masses, moments of inertia, and mass center locations were calculated from a mathematical model developed by Hanavan[89]. Segmental masses were reported by Dempster[90]. Those along with the participants' anthropometric data provided the magnitude and location of segmental masses, mass centers, and segmental moments of inertia. The center of pressure of the foot was then calculated using ground reaction forces measured from the force plate. Accuracy is within 0.003m, which results in only a

4% error in prediction of lower extremity torques[91]. Inverse dynamics were then applied using both linear and angular Newtonian physics to calculate horizontal (Ky) and vertical (Kz) joint reaction forces and moments of the ankle, knee, and hip during stance phase.

Second, individual forces of the quadriceps, hamstrings, and gastrocnemius were calculated using a mathematical equation. For the equation, the tibia was defined as the line between the ankle and knee, and the femur was defined as the line between the knee and the hip. Anterior shear force of the knee was a force directed perpendicular and anterior to the tibia. Force in the triceps surae (combination of gastrocnemius and soleus) was calculated from plantar flexor torque at the ankle assuming the dorsiflexors were not co-contracting. This method is supported in multiple locations in the literature[39,92]. The specific force of the gastrocnemius (G) was then elicited as a function of the cross-section of the gastrocnemius versus the entire triceps surae. The direction of G was determined from the heel and knee marker positions and was expressed as $\alpha$, the angle between G and the tibia. Hamstrings force (H) was calculated from the extensor torque at the hip joint during the first half of stance. This method was supported by literature that shows a strong association between hip extensor torque and hamstrings EMG activity in early stance[93,94]. The direction of H was a line parallel to the femur at an angle $\beta$ to the tibia. Quadriceps force (Q) was calculated from the observed net torque at the knee and the gastrocnemius and hamstrings forces because the net torque at the knee is a function of all muscles that cross the joint as represented by the equation:

$$Kt = Q\,(Qd) - H\,(Hd) - G\,(Gd)$$

where Kt is the net torque of the knee and Qd, Hd, and Gd are the lever arms of the quadriceps, hamstrings, and gastrocnemius, respectively. The direction of Q ($\phi$) was determined from the literature, and is also a function of the knee angle[95,96]. The forces of the lateral support structures (Lss) were calculated in similar fashion, although there is no associated angle with them. Knee compressive force (Kc) was calculated with the following equation:

$$Kc = G\cos(\alpha) + H\cos(\beta) + Q\cos(\phi) - Kz\cos(\lambda) + Ky\sin(\lambda) + Lss$$

Each predicted muscle force and its associated angle are represented in the figure below.

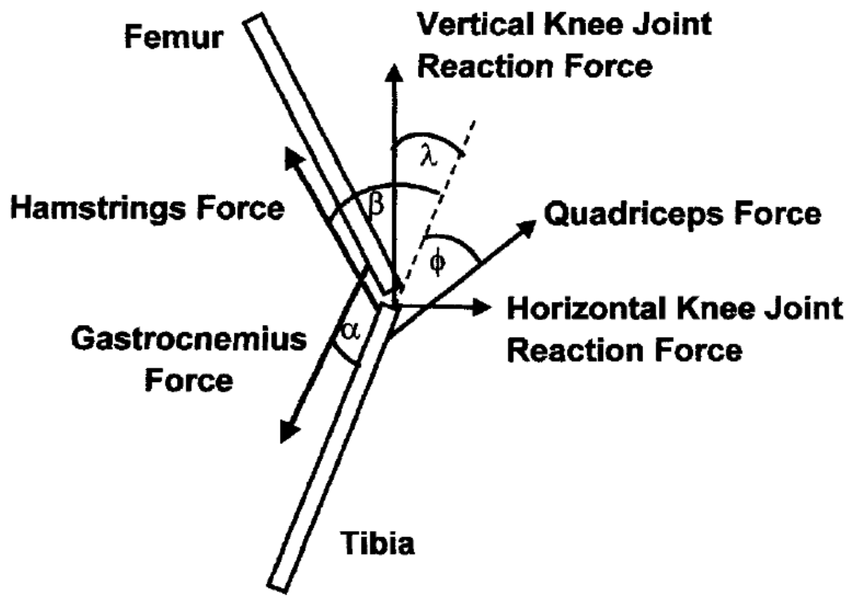


Figure 3: Knee Model

***Knee Stiffness Measures***

Knee stiffness is found by dividing the change in internal knee extensor moment by the change in knee angle, so maximum knee stiffness was calculated during the first 50% of stance phase when the maximum change in extensor moment and maximum change in knee angle happened within 10% of each other.

***Training Behaviors and Injury History Measures***

Training behavior and injury history information was collected at baseline. Training behavior information collected included weekly mileage, years running, average training pace, shoe mileage before replacement, shoe type, time spent cross training, time spent running on different surfaces, and stretching behaviors. Injury history was also collected at baseline. Data collected included past injuries, current running-related problems, and whether or not subjects were injury free for sixth months to be eligible for enrollment. Follow-up visits included an abbreviated version of the baseline data collected for statistical analyses.

***Psychosocial Measures***

<u>SF-12 Short Form Health Status Questionnaire:</u>

SF-12 is an abbreviated measure of perceived health status derived from the longer SF-36. It was developed from the Medical Outcomes Study[97]. SF-36 provides perceived quality of life over 8 subscales: physical function, role limitations due to physical problems, bodily pain, general health, vitality, social function, role limitations due to emotional problems, and mental health[98]. SF-12 is a shorter 12-item self-report survey that yields a summary measure of two subscales: physical and mental health. Each component is reported separately, and each has achieved multiple R squares of 0.911 and 0.918 in predictions of the full SF-36 score, indicating that the abbreviated version yields reliable measures. The mental component provides information about perceived mental health, or a person’s overall impression of their mental health status. The physical component provides information about perceived physical functioning. Both are on a scale of 0 (low) to 100 (high).

Positive and Negative Affect Schedule (PANAS):

The PANAS is a 20-item self-report measure to assess current positive and negative affect[99]. Each affect score is determined by answers to two 10-item subsections. PANAS focuses on affect over the past week using a scale of 1 = very slightly or not at all, 2 = a little, 3 = moderately 4 = quite a bit, and 5 = extremely. Subjects with a high positive affect exhibited more feelings such as enthusiasm, inspiration, or excitement during the past week. Subjects with a high negative affect exhibited more feelings such as nervousness, jitteriness, or distress during the past week. The scale has been shown to be valid in measuring general distress, dysfunction, and depression.

Satisfaction with Life Scale (SWL):

The SWL is a 5-item questionnaire to assess an individual's overall judgment of global life satisfaction. Developed by Diener et al.[100], it allows subjects to weight the importance of different domains according to their own values using a scale from 1 (strongly disagree) to 7 (strongly agree). Total scores range from 5 (extremely dissatisfied with life) to 35 (extremely satisfied with life).

State-Trait Anxiety Inventory Scale (STAI-S):

Subjects answered 20 questions about their current state on a scale from 1 (almost never) to 4 (almost always). Statements ranged from, "I feel calm," to, "I feel stressed." A score from 20-80 is derived from the answers. This scale was developed by Spielberger et al.[101] and represents the subjects total anxiety level with 20 representing no anxiety at all and 80 representing extreme anxiety.

Runners’ Adherence Self-Efficacy:

The confidence of a runner to maintain their running behavior was shown to be an important factor in predicting a runner’s capability to maintain training behavior[15]. This scale assesses the runner’s self-efficacy to continue running for one week and each consecutive week up to eight weeks.

Visual Analogue Scale (VAS):

VAS was used to assess pain from 0 (no pain) to 10 (extreme pain).

## **Statistical Analysis**

This study looked at baseline data of the TRAILS cohort. 159 participants were included, 58 of which reported an anterior knee pain injury of grade I or greater. Statistical analyses were done with SAS or S-plus at the 0.05 two-sided significance level. The statistical analysis for this arm of the study involved two parts: a bivariate analysis followed by a multivariable logistic regression model.

For the bivariate analysis, we tested whether a specific biomechanical, anthropometric, training, or psychosocial variable could predict an anterior knee pain injury. Training pace and body weight were included as covariates for the biomechanical variables. Variables that were significant in the bivariate analysis ($p<0.05$) were included as independent variables in a multivariable logistic regression model with injury as the dependent variable. Training pace and body weight were included as covariates for the biomechanical variables.

The injured group had a different number of injuries on the dominant and non-dominant sides. To ensure that any difference observed was not due to side of injury (i.e., group difference in flexibility because the injured group had more non-dominant side injuries), we sampled dominant and non-dominant sides from the uninjured group at the same ratio as the injured group. We repeated this ten times so that there was no sampling bias from a single run of the procedure.

Once we had our ten data sets, we ran a multiple imputations procedure called MIANALYZE to calculate the mean, standard error, and p-value. Instead of imputing one value, we imputed all ten values from our data sets. The standard error was found by taking into account the variance from all ten of the artificially created data sets. P values were calculated using the adjusted variances.

## Results

Of the 300 participants in the TRAILS cohort, 159 participants were analyzed. Runners enrolled in the TRAILS cohort that experienced an anterior knee pain injury of grade I or greater (N=58) constituted the Injured group. Runners that enrolled in the TRAILS cohort and remained injury free (N=101) constituted the Uninjured group. To qualify as experiencing an anterior knee pain injury, participants must have had a singular injury of anterior knee pain without any other injury present. Participants that experienced anterior knee pain more than once and separately were only included in the injured group one time. The study diagram is shown below.

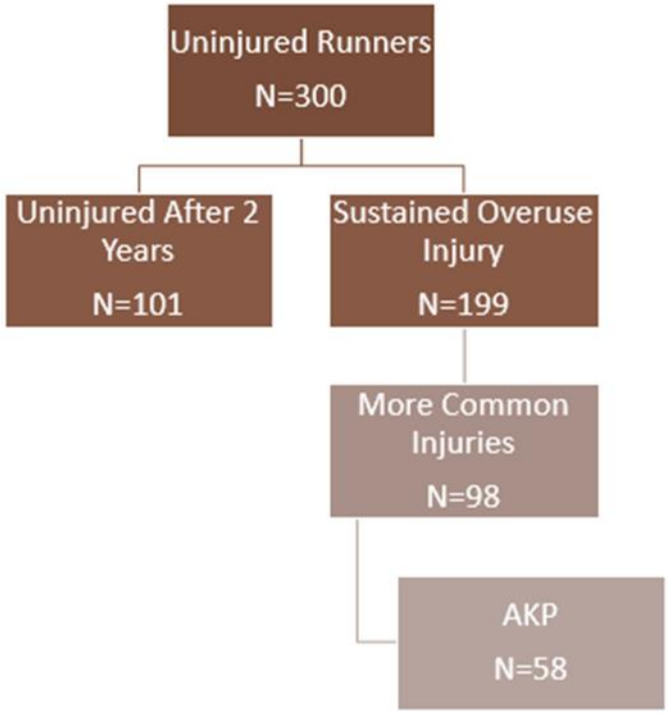


Figure 4: Study Design

***Bivariate Analysis***

Females accounted for 45.31% (N=29) of the injured group and 54.69% (N=35) of the non-injured group. Average age was 42.1 ± 10.3 years for the injured group and 40.0 ± 10.3 years for the uninjured group. Both groups reported similar training regimens, and training behavior was not a significant predictor of injury. Weekly mileage for both groups was 20 miles per week and training pace was 9 min/mile. Both groups had 12 years of running experience, and about half of both groups had a previous running-related injury. See Table I for further demographics and training variables.

Table I: Participant and Training Behavior Characteristics Used to Predict Injury

| | Injured Runners (N=58) | Uninjured Runners (N=101) | Significance (p) |
|---|---|---|---|
| Characteristic | Mean (% or SD) | Mean (% or SD) | |
| Gender n,(% female) | 29 (45.3) | 35 (54.7) | 0.06 |
| Age | 42.05 (10.3) | 39.99 (10.3) | 0.23 |
| Height (m) | 1.71 (0.1) | 1.74 (0.1) | 0.12 |
| Weight (kg) | 70.63 (13.5) | 74.37 (14.6) | 0.11 |
| BMI (kg/m$^2$) | 23.98 (3.6) | 24.52 (3.4) | 0.35 |
| Miles/week | 18.92 (10.2) | 19.91 (14.5) | 0.65 |
| Training pace (min/mile) | 8.98 (1.3) | 8.86 (1.2) | 0.55 |
| Years Running | 11.14 (10.0) | 11.90 (9.3) | 0.63 |
| Previous Injury, n (%) | 44 (40) | 66 (60) | 0.17 |
| Light/Minimalist Shoe, n (%) | 37 (38.1) | 60 (61.9) | 0.59 |
| Motion/Stability Shoe, n (%) | 21 (34.0) | 41 (66.1) | |

Q-angle, arch index, and flexibility (quadriceps, hamstrings, and ankle) were not significant predictors of injury. Strength characteristics were similar between groups after adjusting for sex and body weight. Hip abductor, knee flexor, knee extensor, and ankle plantar flexor strength were non-significant as predictors of injury. See Table II for further anthropometric and strength characteristics.

Table II: Anthropometric and Strength Characteristics Used to Predict Injury. Strength variables adjusted for gender and weight.

| | Injured Runners (N=58) | Uninjured Runners (N=101) | Significance (p) |
|---|---|---|---|
| Characteristic | Mean (% or SD) | Mean (% or SD) | |
| Anthropometric | | | |
| Q- angle, deg | 14.0 (7.0) | 12.8 (7.1) | 0.31 |
| Arch Index | 0.2 (0.1) | 0.2 (0.1) | 0.86 |
| Quadriceps flexibility, deg | 54.1 (8.8) | 54.8 (7.7) | 0.59 |
| Hamstrings flexibility, deg | 157.5 (11.8) | 155.3 (12.8) | 0.29 |
| Plantar flexion flexibility, deg | 14.6 (6.2) | 15.7 (5.8) | 0.26 |
| Dorsiflexion flexibility, deg | 41.0 (6.7) | 40.28 (7.25) | 0.53 |
| Strength | | | |
| Hip abductors, N*m | 75.3 (22.5) | 78.09 (19.16) | 0.77 |
| Knee extensors, N*m | 86.7 (39.6) | 95.63 (40.09) | 0.85 |
| Knee flexors, N*m | 54.5 (21.1) | 57.70 (19.14) | 0.87 |
| Knee flexion/extension ratio | 0.7 (0.3) | 0.65 (0.19) | 0.54 |
| Ankle plantar flexors, N*m | 39.4 (15.9) | 40.33 (14.85) | 0.65 |

The mental component of SF-12 was predictive of anterior knee pain injury. Runners who became injured reported worse mental health-related quality of life compared to the uninjured group. Other psychosocial outcomes were not predictive of injury. Injured and uninjured runners reported similar pain, positive and negative emotions, satisfaction with life, and exercise self-efficacy. See Table III for further psychosocial characteristics.

Table III: Psychosocial Characteristics Used to Predict Injury

| | Injured Runners (N=58) | Uninjured Runners (N=101) | Significance (p) |
|---|---|---|---|
| SF-12 (0-100) | | | |
| Physical | 56.0 (2.5) | 55.8 (1.7) | 0.45 |
| Mental | 47.3 (6.2) | 49.5 (3.2) | 0.01 |
| PANAS (10-50) | | | |
| Positive affect | 37.9 (6.0) | 38.9 (4.9) | 0.27 |
| Negative affect | 14.6 (3.8) | 13.6 (3.0) | 0.07 |
| STAI-S scale (20-80) | 29.2 (7.1) | 27.8 (5.8) | 0.36 |
| Exercise Self-Efficacy (0-100) | 97.3 (5.3) | 97.9 (6.0) | 0.58 |
| Visual analog scale for pain (0-10) | 0.7 (1.1) | 1.1 (1.2) | 0.21 |
| Satisfaction with life (5-35) | 28.8 (4.0) | 29.1 (5.1) | 0.63 |

Knee stiffness was a significant predictor of injury. Runners who experienced an AKP injury had significantly greater knee stiffness at baseline than uninjured runners. Other biomechanical factors were not predictors of injury. Injured and uninjured runners had similar vertical impact peak force, braking force, propulsive force, tibial and patellofemoral compressive forces, and knee abduction and extension moments. See Table IV for further biomechanical force characteristics.

Table IV: Biomechanical Force Characteristics Used to Predict Injury. Adjusted for pace and weight.

| | Injured Runners (N=58) | Uninjured Runners (N=101) | Significance (p) |
|---|---|---|---|
| Characteristic | Mean (SD) | Mean (SD) | |
| Vertical impact peak, N | 1037.5 (288.9) | 1093.1 (244.0) | 0.82 |
| Vertical propulsive force, N | 1592.0 (326.8) | 1676.5 (300.3) | 0.50 |
| Braking force, N | 206.1 (56.6) | 214.5 (50.1) | 0.36 |
| Propulsive force, N | 178.5 (40.6) | 190.6 (42.5) | 0.10 |
| Tibial compressive force, N | 6692.3 (1608.3) | 7116.0 (1551.2) | 0.61 |
| Patellofemoral compressive force, N | 2874.6 (972.0) | 3106.1 (897.6) | 0.54 |
| Knee abduction moment, N*m | -67.0 (30.0) | -72.8 (27.0) | 0.74 |
| Knee extension moment, N*m | 144.8 (50.0) | 150.5 (44.1) | 0.61 |
| Max knee flexion, deg | 40.7 (5.4) | 40.3 (4.8) | 0.72 |
| Knee stiffness, N*m/deg | 7.1 (2.8) | 6.7 (2.0) | 0.02 |
| Knee power absorption, W | -570.8 (215.4) | -591.1 (198.5) | 0.85 |
| Knee negative work stance, J | -31.5 (12.7) | -33.1 (11.7) | 0.98 |

Rearfoot motion variables were also similar between groups. Both groups had a touchdown angle of 6.6 degrees supinated, a maximum eversion of -7 degrees, and maximum eversion velocities of about -200 deg/s. See Table V for further rearfoot motion characteristics.

Table V: Rearfoot Motion Characteristics Used to Predict Injury

| | Injured Runners (N=58) | Uninjured Runners (N=101) | Significance (p) |
|---|---|---|---|
| Characteristic | Mean (SD) | Mean (SD) | |
| Touchdown angle, deg | 6.6 (3.9) | 6.6 (3.6) | 0.10 |
| Maximum eversion, deg | -7.8 (3.9) | -7.3 (3.4) | 0.49 |
| Eversion range of motion, deg | 14.3 (3.9) | 13.9 (3.7) | 0.51 |
| Maximum eversion velocity, deg/s | -200.9 (73.5) | -186.3 (60.3) | 0.23 |
| Forefoot adduction, deg | -3.5 (6.5) | -4.7 (6.5) | 0.31 |
| Strike index, % distance from heel | 0.1 (0.2) | 0.1 (0.2) | 0.94 |

***Multivariate Analysis***

Variables that were significant in the bivariate model were entered into a multivariable logistic regression model. The two variables that were included were maximum knee stiffness and the mental component of SF-12. The mental component of SF-12 remained significant after the multivariable model, indicating that runners who sustained an AKP injury reported significantly worse mental health-related quality of life even after accounting for all other variables.

Table VI: Parameter Estimates for Multivariable Analysis

| Parameter | Estimates | 95% Confidence Limits | | Pr > \|t\| |
|---|---|---|---|---|
| Maximum Knee Stiffness | 0.087 | -0.06493 | 0.23984 | 0.26 |
| MC SF-12 | -0.084 | -0.15874 | -0.00908) | 0.03 |

## Discussion

The purpose of this study was to determine the risk factors that predict AKP in habitual runners. This information could be useful in treating injured runners and to prevent future knee injury.

We examined runners from the public health perspective using community recreational runners as opposed to elite competitive runners. Our results are generalizable to the 60 million Americans who consider themselves recreational runners.

Running over 40 miles per week is often cited as a threshold for injury risk[22]. However other studies showed no difference in weekly mileage between injured and uninjured runners[47], or that injured runners actually ran less than uninjured runners[25]. Our results indicated that weekly mileage was not a risk factor for AKP.

Anthropometric measurements are often measured as potential risk factors for running injuries. Vitez et al[102] found a relationship between injured runners and BMI in a recent study examining marathon runners. His team proposed that the mechanism of injury was the added joint stress due to excess weight. Q-angle is also commonly measured as a potential risk factor. Caylor et al[30] found in a systematic review that the relationship between q-angle and injury is equivocal. Our results indicated that there is no significant relationship between Q-angle and AKP.

Lack of muscular strength has been proposed as a risk factor for injury. The potential mechanism is that decreased muscular strength leads to less shock absorption during the support phase, resulting in greater joint loads and eventual overuse injury[12]. Our results showed no difference in muscular strength between groups. Messier et al[15] proposed a theory that neuromuscular control may be more important than strength alone, but it is yet to be analyzed.

Hreljac[9] posits that high ground reaction forces in runners with little time between impacts leads to injury. In a separate study, Hreljac et al[103] showed that injury-free runners had lower peak vertical ground reaction forces and lower loading rates. In contrast, multiple studies from our group indicate that uninjured runners actually had greater ground reaction forces than injured runners[64,104]. When examining all overuse running injuries, there was no significant difference in vertical ground reaction forces between injured and uninjured runners[15]. Our analysis showed that ground reaction forces were not significant risk factors for AKP.

Rearfoot motion, while oftentimes not a significant risk factor[15,105], is still measured in most injury-related biomechanical studies. When examining all overuse running injuries, the TRAILS cohort showed that rearfoot motion was not a significant risk factor[15]. Our results agree. We found no difference in rearfoot motion between AKP and uninjured runners.

Knee stiffness was a significant predictor of AKP in the bivariate analysis ($p=0.02$). Farley et al.[106] characterized the knee as a spring dissipating energy during footstrike. Unfortunately, in knees with greater stiffness, the ability to dissipate energy is diminished. That may lead to overuse injury. Messier et al[15] found that knee stiffness is more closely related to injury in runners with greater body weights (>80kg). This could indicate why stiffness was no longer significant after our multivariable analysis; the body weight means of the injured and uninjured groups were 71kg and 74kg, respectively.

### *Comparison to All Overuse Running Injuries*

Our multivariable analysis showed that runners who reported a lower mental health-related quality of life were diagnosed with AKP more often than runners with higher values (p=0.03). The negative affect score of the PANAS scale in the bivariate analysis also approached statistical significance (p=0.07). These results align with a previous study examining the risk factors for runners diagnosed with any type of overuse injury[15]. That analysis showed both the mental component of the SF-12 and negative affect were significantly different between injured and uninjured runners. Our study had a similar design but examined only the most common overuse injury, AKP. When preventing injury, these data show that clinicians should be examining the mental health status of their patients, as mental health outcomes significantly predicted injury in both studies.

It is important to note that data from our study and the study examining all overuse running injuries[15] come from the same cohort of runners. There are both pros and cons to using the same cohort. Because the results of the two studies were so similar, examining just one overuse injury with the same cohort validates the results of the analysis of all overuse injury. Runners that experience AKP are similar to runners that experience any kind of overuse injury. From a clinical standpoint, this indicates that AKP can be treated in the same fashion as any overuse running injury. However, some would argue that our results were similar *because* we used the same cohort; even if AKP behaves differently from all overuse injuries, we would not have seen a difference because the cohort was the same. One way to definitively know whether AKP behaves similar to or differently from all overuse injuries would be to replicate this study with a different cohort of runners.

Contrary to other running studies that found significant biomechanical differences between injured and uninjured runners[15,35,47,64,107], significant predictors of AKP were limited to one psychosocial variable in our study. It was somewhat surprising that many of the risk factors cited in other studies were not significant in our study. This could be attributed to a difference in study design. More specifically, the TRAILS study was one of only a few studies that utilized a prospective design[23,37,108]. Many studies utilized a retrospective or cross-sectional design[7,16,22,47,64] which is inherently susceptible to bias.

The TRAILS study also included a control group. We observed runners over two years and separated them into groups based on their injury status (injured or uninjured). Having a control group decreases the variance between groups and allows us to identify differences that could lead to injury.

Our study also examined a wide breadth of variables, including anthropometrics, training variables, strength and flexibility, gait, physiologic, and psychosocial factors. This is different from other studies that focused on one subset of variables, be it biomechanical, physiologic, or anthropometrics. All of these differences could explain why our results are different than the results of other studies.

### *Psychosocial Discussion*

Frederickson and Branigan[109] propose that negative emotions limit the attentional focus of the subject. This narrowed focus can decrease a runner's awareness of physiologic cues; for example, they may not be as aware of soreness or tightness in the lower extremity that could be indicative of injury. This decreased awareness could lead to injury. Our results and the results of the TRAILS cohort show that runners who become injured experience negative emotions and worse mental health-related quality of life. This could explain why they became injured; their negative emotions may have caused them to be less aware of factors indicating their injuries. To test the plausibility of this theory, future studies should consider including an attentional awareness measure.

A more simple explanation postulated by Messier et al[15] is that runners with worse mental health-related outcomes tend to exceed their limits or take fewer precautions in regards to injury. While little data exists, psychosocial variables do appear to have an effect on running-related injuries.

***Future Research***

The lack of significant biomechanical variables from our multivariable analysis was surprising. Despite our multivariable approach and our study design, no biomechanical variables were significant risk factors for AKP. It is possible that the offending variable(s) were not measured. Studies that have documented biomechanical variables as risk factors explain little of the variance between injured and uninjured runners. Messier et al[15] found that maximum knee stiffness was a significant risk factor, but it only explained 12.3% of the variance between groups, indicating that other variables led to injury. Napier et al[110], found that 34-57% of the variance in kinetic outcomes in female runners was due to kinematic variables. While the explained variance is better than in the Messier study, it indicates that other factors were involved that were not examined.

Another possibility is that differences between injured and uninjured runners occur at the tissue level. Messier et al[15] speculated that runners who become injured may have muscle tissues that are less resistant to the high-magnitude, frequently applied loads that come with running. While this remains a possibility, tissue characteristics are difficult to measure.

Despite the countless variables that may cause injury, our results indicate that the psychosocial component is a risk factor for overuse running injuries. When creating an intervention to reduce or prevent running injuries, including a psychosocial component appears essential.

This study provides useful information on the health outcomes of habitual runners in the general population. Based on the data, we know that psychosocial factors play a role in overuse injury. We also know that biomechanical and anatomic factors may not play as large a role as once believed. From this, clinicians can treat AKP just like they would treat any overuse injury. Instead of having to tailor rehabilitation programs to AKP specifically, it is possible that a more general rehabilitation protocol for any overuse running injury would be appropriate for runners with AKP. In addition, this study shows that preventing overuse injury may be more about improving a person's psychological state than correcting any anatomic or biomechanical differences.

### *Limitations*

As mentioned previously, this study only measured variables at baseline. While that is appropriate for the analysis at hand, we cannot know if the variables changed from baseline to the point of injury. Additionally, because this study focused on injury as a public health problem, we did not exclusively examine runners with extreme values. Risk factors that are not significant for the overall analysis may be important for individuals with more extreme values. Future studies could analyze this subgroup of runners with extreme values to see if they experience risk factors differently. Furthermore, many of our training variable data were self-reported, and it is important to note that self-report data have their own inherent bias.

## Conclusions

The results of this study indicate that runners with lower mental health-related quality of life are at increased risk of AKP. Biomechanical, training, and physiologic variables were not significant risk factors. Future running injury prevention studies should include a psychological intervention. In the treatment of AKP, a protocol generalizable to any overuse running injury should be appropriate to treat AKP. Prevention of AKP should focus on a runner's psychological state as opposed to any biomechanical differences.

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# <u>Curriculum Vitae</u>

# Mark K. Matechik, MS, ACSM-CEP

## PROFESSIONAL EXPERIENCE

CLINCIAL COMMUNITY BASED EXERCISE PROGRAM STAFF and
CERTIFIED CLINICAL EXERCISE PHYSIOLOGIST
August 2017 to Present
**Wake Forest University Department of Health and Exercise Science –** Winston-Salem, NC
Supervised participants in a medically based chronic disease prevention program. Responsibilities include:

- Monitor patients' medical status during exercise through EKG telemetry, assessment of vital signs, and regular check-ins
- Respond appropriately to emergency situations involving patients by treating on-site or notifying emergency medical services
- Perform annual physician-monitored EKG stress tests on participants to determine appropriate exercise prescriptions
- Provide strength training and Silver Sneakers classes for participants

GRADUATE RESEARCH ASSISTANT
October 2017 to Present
**Wake Forest University-** Winston-Salem, NC
Staff member on four research grants.

- Weight Loss and Exercise for Communities with Arthritis in North Carolina (P.I. Dr. Stephen Messier, funded by NIH)
    - Perform baseline and follow-up assessments of participants for data analysis
    - Collect and enter data into online database
    - Perform double data entry to check for accuracy
- Strength Training for Arthritis Trial (P.I. Dr. Stephen Messier, funded by NIH)
    - Process 3-D gait data in Cortex system for statistical analysis
- Strength Training and Running Study (P.I. Dr. Stephen Messier, funded by US DoD)
    - Lead interventionist for strength training group
    - Guided participants through 18-month exercise program, including strength, flexibility, and neuromuscular training
    - Assisted lab staff in data collection using 3-D gait analysis
- Nitrate and Exercise Performance in Middle to Older Aged Adults (P.I. Dr. Michael Berry, funded by Isagenix International LLC)
    - Certified Clinical Exercise Physiologist on staff
    - Monitor patients' health status during baseline maximal exercise tests using EKG telemetry and vital assessments
    - Responsible for termination of maximal $VO_2$ assessments when medically appropriate

GRADUATE TEACHING ASSISTANT AND COURSE INSTRUCTOR
August 2017 to Present
**Wake Forest University Department of Health and Exercise Science –** Winston-Salem, NC
Instructor for HES 101 Exercise for Health and Graduate Teaching Assistant for HES 370 Biomechanics of Human Movement. Responsibilities included:

- Led 10 sections of 16 students in HES 101 with the goal of improving students' knowledge of exercise so they could better incorporate it into their lives to reduce the risk of chronic disease
- Led weekly class and lab times to teach both the scientific and practical basis of exercise
- Completed six formal graduate and post-doc student teaching workshops through the WFU Teaching and Learning Center
- Led three sections of HES 370 labs with the main purpose of running a student-led biomechanical gait analysis project

- Assisted students with filming and processing data to learn biomechanical measurements and data processing

## EDUCATION

**Master of Science: Health and Exercise Science** August 2017-May 2019

**Wake Forest University –** Winston-Salem, NC

- Emphasis in biomechanics and randomized clinical trials
(Primary Advisor: Dr. Stephen Messier, PhD │ Professional Mentor: Dr. Peter Brubaker, PhD)
- Award recipient of full-ride scholarship and Provost scholarship
- Course work: Epidemiology, clinical research methods, cardiac pathophysiology, special populations exercise testing and prescription, biomechanics
- **Thesis**: A 2-year Prospective Cohort Study of Anterior Knee Pain in Runners

**Florida State University College of Medicine --** Tallahassee, FL May 2015-July 2016

- Course work: Pharmacology, pathology, anatomy, physiology, microbiology of the immune, nervous, reproductive, gastrointestinal, and cardiopulmonary systems

**Bachelor of Science: Exercise Science** August 2011-May 2015

**Florida State University --** Tallahassee, FL

- Member of Garnet and Gold Scholars, National Merit Scholar, Cum Laude