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RESEARCH ARTICLE

The Frontal and Transverse Plane Kinematics of the Ankle and Knee in Healthy 18-25 Year Olds with Differing Foot Strike Patterns During Treadmill Running

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Abstract

Purpose: To compare ankle and knee frontal and transverse plane kinematic variables of rearfoot striking (RFS) and forefoot striking (FFS) patterns while running on a treadmill.

Methods: Twenty-one healthy individuals (21.2 ± 1.4 years old) participated in the study. Vicon® motion analysis technology captured subjects' RFS and FFS running patterns. A one-way ANOVA test was used to analyze differences between RFS and FFS variables.

Results: Ankle eversion excursion ($p = 0.036$) and tibial rotation excursion ($p < 0.001$) were greater in the RFS group compared to the FFS group. There was no significant difference in knee abduction between the two groups.

Conclusion: Frontal and transverse plane excursion is greater in RFS than FFS in the lower leg and ankle. Patients with injuries vulnerable to excessive excursion of the knee in the transverse plane (tibial rotation) or the ankle in the frontal plane (ankle eversion) may benefit from switching to a FFS pattern.

Keywords: Running Mechanics; Frontal Plane; Transverse Plane; Biomechanics

Introduction

In recent years, recreational running has grown in popularity. It has been reported that 10-20% of Americans run regularly for recreational purposes [1]. These runners have a variety of foot strike patterns. Rearfoot and forefoot strike patterns are the two most common types of foot strikes. Approximately 75% of runners make initial contact with a rear foot striking pattern [2]. Runners' foot strike patterns have a profound effect on the manner in which ground reaction forces are dispersed throughout the body. Midfoot and forefoot striking patterns have been shown to significantly reduce vertical impact peak forces and net knee extensor moment [2,3]. A combination of foot strike, kinematic, and gender factors can influence the likelihood of acquiring an injury. One study stated that 50% of Americans who run will experience running related injuries at some point, with 25% of them having a current injury at any given time [1].

Up to 65% of runners sustain an overuse injury that causes them to seek medical attention or stop running [4]. The two most common sites of running injuries are the knee and ankle. The knee was found to be the most commonly injured joint from running in males, whereas the ankle/foot was most common in females [5]. Typical running injuries are medial tibial stress syndrome (MTSS), plantar fasciitis, and posterior tibial tendon dysfunction (PTTD). MTSS affects between 5%-35% of runners. Running downhill and frequent shoe changes can increase the chance of acquiring MTSS [6]. Plantar fasciitis is most commonly caused by overuse rather than a single traumatic event [7]. Rearfoot valgus and varus, which occur in the frontal plane, each cause positional changes upward in the kinematic chain. Valgus can lead to increased stress on the ankle invertors, which can lead to PTTD. In its early stages, PTTD has also been identified as a common running-related injury [8]. Rearfoot varus can also be problematic, as it contributes to a higher arch and increased rigidity of the foot and ankle and decreases force attenuation, which can lead to injury [9].

The inherent kinematics of different foot strike patterns alters the likelihood of running pathologies. A previous study found that foot strikes and repetitive plantar loads have been commonly associated with lower limb injuries, especially running- related injuries, such as medial tibial stress syndrome, patellofemoral pain syndrome, and plantar fasciitis [4,7,9]. Forefoot and rearfoot patterns may only differ in the foot by a few inches; however, the difference has a profound effect on the kinematic chain. With forefoot striking, the foot tends to be more plantarflexed and the knee more flexed than in rearfoot striking, which has been associated with decreased hip and knee loads [3]. Researchers have determined numerous factors, including ankle kinematics that can predispose an individual to such an injury as patellofemoral syndrome [9]. Duffey, *et al.*, concluded that higher arched feet, weaker knee extensors, and less foot pronation in the first 10% of stance could increase a person's likelihood of injury [4]. Barton, *et al.*, was able to relate a small reduction in rearfoot eversion excursion in the first 10% of stance, significant increases in rearfoot excursion at heel strike, as well as other factors as possible predictors and reasons for patellofemoral pain [10].

The previous research conducted on running styles has developed general themes in kinematic literature. One of these themes suggests that the ankle and knee are interrelated, and an alteration at one joint will cause an alteration at the other [3]. This theme is the driving force behind analyzing rearfoot and forefoot striking patterns and the subsequent effects on the ankle and knee. The majority of prior research focused mainly on the sagittal plane of motion. Research is limited in frontal and transverse planes and their involvement in running-related injuries. Altering foot strike patterns affects the kinematic chain; therefore, it is important to analyze how this data can be interpreted to determine the likelihood of specific running related injuries. The majority of studies analyzed kinematics using force plates and motion-analysis cameras on level ground at an instantaneous point in time [11,12]. However, individuals may alter their running gait when targeting a force plate in the floor. A finite number of studies use a treadmill as the running medium to analyze kinematics over continuous gait cycles and therefore obtain a more accurate representation of the running pattern. This study attempted to record the frontal plane variables of the knee and ankle along with tibial internal rotation in the transverse plane via motion analysis technology while having subjects run for a short duration demonstrating each of the striking patterns. Tibial internal rotation was assessed and is expected with greater degrees of ankle frontal plane motion (eversion), as studies have shown these motions to be coupled [13]. Therefore, the purpose of this study was to determine common frontal and transverse plane kinematics in rearfoot and forefoot striking patterns while running on a treadmill. It is hypothesized that ankle and knee kinematic variables will differ between foot strike patterns, which may then be linked to existing predictors of running-related injuries.

Methods

Twenty-one students from a small private university between the ages of 18 to 25 were subjects in this study. To be included in the study, the subjects must have met the following criteria: no lower extremity injuries within 6 months or undergone orthopedic surgery on the lower extremities within the past year prior to testing that could limit them from activity participation; no cardiovascular compromise or illness at the time of testing that would limit them from being able to run for at least 5 minutes consecutively on a treadmill. Subjects were excluded if they did not meet these requirements. There were no subjects excluded from the study upon initial intake. The institutional review board at Saint Francis University approved the study protocol [14].

Prior to participating, all subjects completed an informed-consent form, a subjective questionnaire form, and a previous injury questionnaire as they arrived in the Human Performance Lab at Saint Francis University. After the forms were completed, a researcher recorded the subject's height, weight, leg length and ankle and knee joint girths. Eighteen reflective markers were placed on the subjects as per Vicon® motion capture system's lower extremity protocol, which included markers on the base of the second ray, lateral malleolus, posterior calcaneus, lateral leg (fibula), lateral femoral epicondyle, lateral thigh, anterior superior iliac spine, posterior superior iliac spine and iliac crest. Initial software setup was completed with a static trial to determine baseline joint angles and calibrate the software.

Prior to testing, subjects were instructed in the testing procedures. The subjects performed a warm-up of self-selected running pace and duration on a treadmill that did not exceed 5 minutes. Following the warm-up, subjects began a 3-minute running trial at a submaximal, self-selected pace (average 2.7 ± .7 m/s). The last 30 seconds of the 3-minute trial was recorded using the Vicon® motion analysis system. The analysis time frame was chosen based on the protocol used in the study by Langley, *et al.*, Following exercise, the subject performed a 2-minute cool-down period at a self-selected slower pace [15].

After the first exercise trial, the preferred foot strike pattern (forefoot or rearfoot strike) of the subject was determined by researcher observation and review of the motion analysis data. Once the subject's preferred pattern was determined, the subject was verbally instructed to perform the opposite foot strike pattern, supplemented by a slow motion video demonstration. All subjects in this study were natural rearfoot strikers and then were instructed to perform forefoot striking upon the second trial. Each subject was allowed as much time as necessary to practice the opposite striking pattern. Once the subject felt comfortable with the opposite striking pattern and the evaluators determined that the new foot strike pattern was correct, which in this study involved the subject landing on the anterior half of the foot without verbal cues, the subject repeated the exercise protocol detailed above for a second trial [12].

A total of 21 subjects completed the study protocol. One of the subject's data was excluded from data analysis due to technology error during the running trials. Another subject's data was excluded due to reflective marker error during the running trial. The subject sample consisted of six males and 13 females, with an average age of 21.2 years (±1.4 years old). Eight of the 19 subjects had experienced previous running related injuries, of which the knee being the most commonly injured joint in the lower extremity. Self-reported injuries included three unspecified knee injuries, two anterior cruciate ligament (ACL) tears, two meniscus injuries, one report of shin splints, and two unspecified ankle injuries. Of the 19 subjects, 13 of them reported that they were regular runners, averaging 9 miles per week among these subjects (Table 1).

	Male (n=6)	Female (n=13)
Mean Height (m)	1.81 ± 0.08	1.70 ± 0.06
Mean Weight (kg)	84.31 ± 16.01	67.74 ± 7.59
Previous Running Injury	2	6
Regular Runners	1	12

Table 1: Gender Specific Subject Information

During collection, the raw marker data were collected at 120 Hz and filtered using a Woltring digital filter (6 Hz) using the Nexus® software to determine joint trajectories. During analysis, the first 20% of the gait cycle (initial contact to loading response) was averaged over all the subject's cycles for the 30 second trial [16]. This data was used when determining joint angles to get an accurate representation of the subject's loading response during ground impact. Following processing, the numerical data was entered into a researcher's laptop, and mean and standard deviations were calculated for each variable tested using Microsoft Excel. Further statistical analysis was calculated using a one-way analysis of variance (ANOVA) in Minitab 17 to determine whether there were significant differences between the variables when comparing foot strike patterns.

Results

Ankle eversion, knee abduction, and tibial rotation measurements were extracted from the motion analysis data (Table 2). Ankle eversion excursion was significantly less in FFS running (5.59 ± 2.44 degrees) than RFS running (7.25 ± 2.27 degrees) (p=0.036). Minimum tibial rotation was less in subjects during FFS running (2.41 ± 8.14 degrees) than RFS running (-.85 ± 7.20 degrees) (p<0.01), as well as tibial rotation excursion was less in subjects during FFS running (20.56 ± 5.90 degrees) than RFS running (27.22 ± 5.58 degrees) (p<0.01). Figure 1 shows a visual representation of a comparison of these measurements between rearfoot and forefoot striking. No significant differences were found in knee abduction between FFS and RFS running patterns.

	Mean	SD	P-value (difference RFS vs FFS)
Rearfoot Strike			
Ankle Eversion			
Minimum	-2.81	2.16	0.012*
Maximum	4.44	1.71	0.634
Excursion	7.25	2.27	0.036*
Knee Adduction			
Minimum	-2.11	4.11	0.772
Maximum	3.92	4.2	0.359
Excursion	6.03	1.85	0.21
Tibial Rotation			
Minimum	-4.85	7.20	0.006*
Maximum	22.37	5.59	0.737
Excursion	27.22	5.58	0.001*
Forefoot Strike			
Ankle Eversion			
Minimum	-0.85	2.40	0.012*
Maximum	4.74	2.07	0.634
Excursion	5.59	2.44	0.036*
Knee Adduction			
Minimum	-2.51	4.37	0.772
Maximum	2.64	4.31	0.359
Excursion	5.15	2.37	0.21
Tibial Rotation			
Minimum	2.41	8.14	0.006*
Maximum	22.97	5.40	0.737
Excursion	20.56	5.90	0.001*

Table 2: Summary of Lower Extremity Measurements per Foot Strike Pattern (in Degrees)(*denotes significant difference)

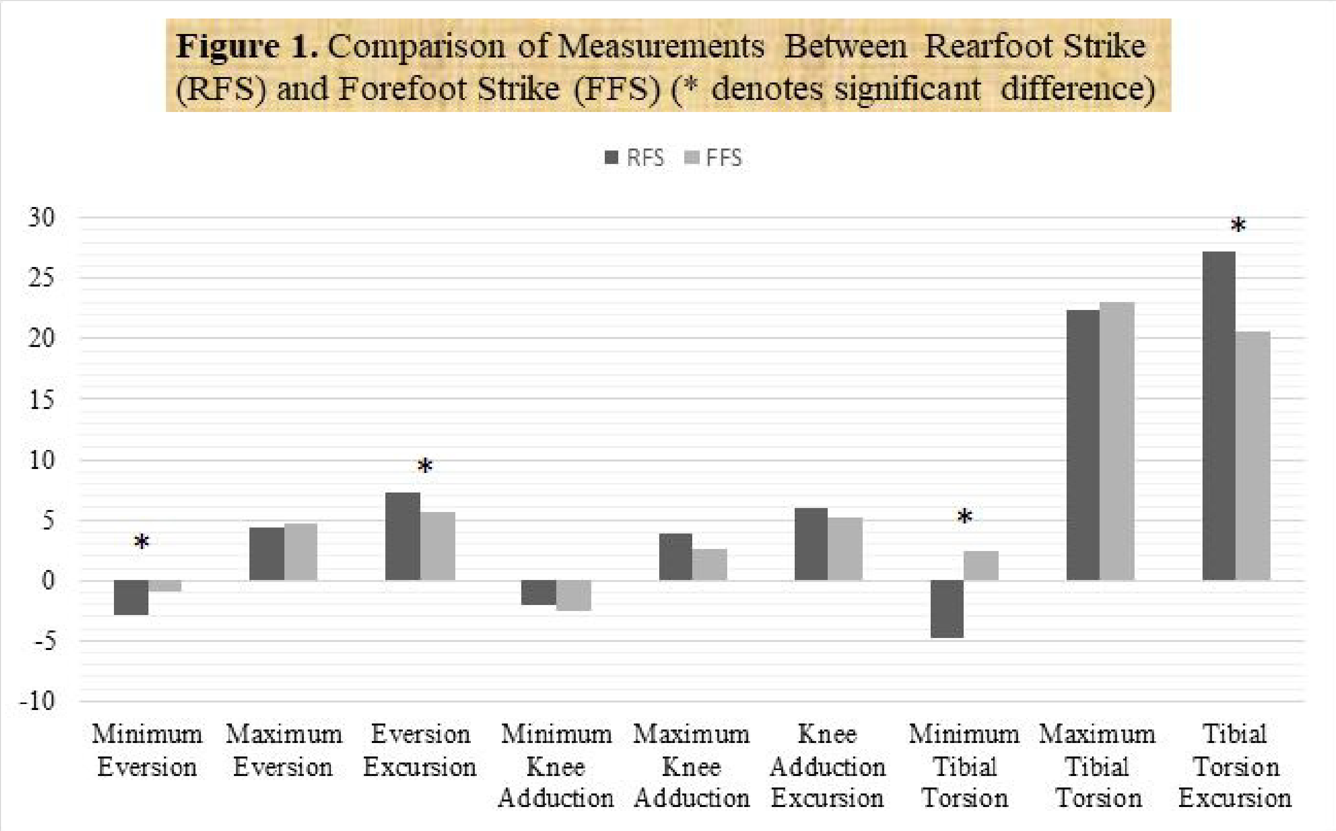

Figure 1: Comparison of Measurements between Rearfoot Strike (RFS) and Forefoot Strike (FFS) (* denotes significant difference)

Discussion

The purpose of this study was to determine frontal and transverse plane kinematics in FFS and RFS while running. It was hypothesized that ankle and knee kinematic variables would differ between foot strike patterns, which may be linked to existing predictors of running-related injuries. Prior research has shown that altering foot strike landing patterns while running can change the joint kinematics of the ankle and knee [2,3]. However, these studies used force plates and predetermined distances to assess subjects' running mechanics. There is currently limited research involving running mechanics and treadmills. McCallion, *et al.,*

Eversion Excursion

This current study found that RFS runners experienced significantly greater eversion excursion (p<0.036) during the first 20% of the gait cycle (initial contact to loading response) compared to FFS runners. Contrary to this study, studies completed by Stackhouse, *et al.*, and Nunns, *et al.,* found higher eversion excursion in FFS when compared to RFS [11,17]. However, some differences exist in the methodology of current study and their studies. The researchers in the Stackhouse, *et al.*, study attached the reflective markers on the calcaneus directly to it by creating a hole in the heel counter of the shoe, and in the Nunns, *et al.*, study the FFS group was barefoot when striking. This current study included the researchers placing the calcaneal marker on the posterior portion of the shoe and allowing forefoot striking to occur while shod. It is possible that these shod individuals experienced less eversion excursion than the previous studies when forefoot striking with some assistance of the footwear. Excessive eversion has been found to be present in individuals at multiple stages of posterior tibial tendon dysfunction (PTTD) [8,18]. The greater eversion excursion range found in this study during RFS has the potential to predispose a runner to injuries involving the invertor musculature such as MTSS and PTTD. If the posterior tibialis were to fatigue and wear over a period of time, a compromised posterior tibialis has been linked to decreased arch height and rearfoot deformities [19]. Additionally, the increased number of females in this study (females = 13, males = 6) and the increased predisposition of females for PTTD, may have contributed to the increased amount of eversion excursion in this study [8,18].

Tibial Rotation Excursion

Greater tibial rotation excursion was also found in the RFS runners compared to the FFS runners (p<0.001). This finding corresponds with the findings of Pohl, *et al.*, who also found that tibial rotation excursion was greater in RFS than FFS [20]. Tibial rotation occurs in the transverse plane and has also been shown to be increased in individuals with posterior tibial tendon dysfunction, secondary to tibial rotation coupling with ankle eversion [21].

Knee Abduction

No significant difference was found in frontal plane knee motion (knee abduction) between the two groups. This is similar to Ness, *et al.*, who found that although there was a difference in PTTD subjects having increased rearfoot eversion compared to normal subjects, there was no difference between knee abduction between the groups [21]. Interestingly, in a meta-analysis of 16 articles comparing studies about biomechanical differences in foot-strike patterns while running, knee abduction was not analyzed [3].

Limitations

This study includes limitations that should be addressed in further research. First, our study only consisted of habitual RFS runners. Further research should incorporate habitual FFS and habitual RFS to determine the mechanical changes between the groups. The subjects tested were all healthy, college-aged students. For a more accurate representation of the general population, a wider age range should be explored. The majority of other research has been done using force plates and does not incorporate a treadmill. McCallion, *et al.,* found in their research that treadmill running alters the foot strike patterns to a hybrid between forefoot and rearfoot [22]. The final study limitation was that this study did not control participant's footwear and their effects on the kinematic chain. However, because participants wore his/her own shoes for both RFS and FFS patterns, and differences were only calculated within subjects, each served as his/her own control.

Over the course of this study, a few sources of error could have influenced the results. The first was error caused by the researchers of the study. For each subject, reflective markers had to be placed in precise locations. To minimize the chance of placement variation, the markers were placed by the same researcher at all times. The other source of error that could have influenced the study is foot striking changes when a person runs on a treadmill compared to a natural surface. As explained previously, research has shown that a runner will exhibit different joint kinematics solely from the surface that is being run on.

Conclusion

In this study, there was a significant difference with ankle eversion excursion in the frontal plane and tibial rotation in the transverse plane motion when comparing rearfoot striking and forefoot striking while running on a treadmill. These differences may contribute to an increased risk for specific running related injuries. Further research is needed to investigate the frontal and traverse plane motions with differing foot strike patterns to determine a possible link with running related injuries. Patients with injuries vulnerable to excess excursion of the knee or ankle may benefit from switching to a FFS pattern while retaining their same footwear. Specifically, these injuries include posterior tibial tendon dysfunction, medial tibial stress syndrome, and anterior knee pain.

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