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THE EFFECTS OF IMPOSED FOOT STRIKE AND FATIGUE ON JOINT STIFFNESS AND METABOLIC COST IN REARFOOT STRIKE RUNNERS

by

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ABSTRACT

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Running research has focused on the effects of acute strike pattern modifications, specifically to lower extremity joint kinetics and stiffness. Joint stiffness may be related to injury risk in runners. As 75% of runners use a RFS pattern, it is worthwhile to study these runners. The purpose of this study was to examine the effects of imposed FFS on ankle and knee joint stiffness before and after a long run in habitual RFS runners. Ankle and knee joint stiffness as well as running economy were measured pre and post fatiguing long run. Ankle joint stiffness was lower during imposed FFS. Knee joint stiffness was higher during imposed FFS. Joint stiffness between strike patterns was independent of fatigue. The RFS pattern yielded better RE than imposed FFS independent of fatigue. Our findings suggest that it would not be mechanically or metabolically beneficial for habitual RFS runners to acutely adopt a FFS.

PREFACE

The findings from this thesis will be submitted for publication to *Medicine & Science in Sport & Exercise* and the formatted manuscript for this journal is presented in Chapter 2.

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ABBREVIATIONS

SSC: Stretch-Shortening Cycle

CMVJ: Countermovement Vertical Jump

RE: Running Economy

RFS: Rearfoot Strike

MFS: Midfoot Strike

FFS: Forefoot Strike

GRF: Ground Reaction Force

ROM: Range of Motion

CHAPTER 1

INTRODUCTION

1.1 Statement of the Problem

In 2013, over 19 million people completed running races ranging from 5k to the marathon (i.e. 26.2 miles). This was a 295% increase compared to 1990 (1). It is evident that distance running is an increasingly popular form of cardiovascular exercise and recreation. There is also a high injury risk associated with running. Between 20-80% of runners suffer a lower-extremity injury, with the knee being the most common location (i.e. 8-50%) (82). In addition, approximately 35-50% (9, 13, 43, 51, 58, 63) of all runners will suffer a stress fracture of the lower limb, and these account for 1-20% of all sports medicine clinic visits (33). As running places repetitive stress on the lower limb, the body's ability to remodel bone and repair soft tissue injuries becomes limited if proper rest is not allowed (2, 74). Inadequate rest coupled with many extrinsic (e.g., training volume, shoe age, foot strike patterns) and intrinsic (e.g., bone geometry & mineral density, anatomical alignment, and previous injuries) factors may contribute to risk of injury (14, 43).

Runners who use a rearfoot strike (RFS) retrospectively report a greater number of injuries than any other strike pattern (19, 81). Approximately 75% of recreational and elite runners use a RFS pattern (44, 56). Scientists, coaches, clinicians and athletes seek to understand how different foot strike patterns change metabolic demands for performance improvements and biomechanical variables that may explain injury risk. For this reason, recent research has focused largely on the biomechanical and metabolic differences between habitual and imposed (i.e. acute transition) foot strike patterns during running (20, 36, 41, 73, 80, 84). Studies have mostly focused on acute comparisons between strike patterns during running efforts in non-fatigued runners although fatigue may yield abnormal running mechanics that could be linked to running injuries (12, 35, 61, 62).

1.2 Literature Review

The first purpose of this literature review is to summarize current scientific findings on biomechanical and metabolic variables associated with different foot strike patterns. The second purpose is to summarize current scientific findings regarding the interaction that fatigue may have on risk of injury and running performance.

1.2.1. Differences in Joint Biomechanics between Foot Strike Patterns

Four types of strike patterns can be used while running: 1) RFS where the heel contacts the ground first, 2) midfoot strike (MFS) where the heel and ball of the foot contact the ground simultaneously, 3) forefoot strike (FFS) where the ball of the foot strikes the ground first followed by a heel drop (11) and 4) toe running where the ball of the foot strikes the ground first and the heel never touches the ground. As toe running is more commonly used during sprinting and is quite rare during distance running, FFS and toe running are most commonly grouped together and referred to as FFS. Strike pattern can be assessed using a number of variables but the most common is the strike index (SI). SI is measured as the location of the stance foot center of pressure (COP) at time of foot strike relative to the foot length and expressed as a percentage (11). Classification of strike pattern is based on specific ranges of SI where 0-33% indicates RFS, 34-67% indicates a MFS, and 68-100% indicates a FFS (3, 11). Foot contact angle at time of foot strike has also been used to assess strike pattern (3). Foot contact angle (FCA) is defined as the sagittal plane angle formed between the foot (i.e. a vector between the fore and rear foot) and the horizontal component of the laboratory coordinate system (i.e. the ground) (3). Classification of strike pattern is based on specific ranges of FCA where RFS corresponds to FCA>8.0°, MFS to -1.6°<FCA<8.0°, and FFS to FCA< -1.6° (3). This method correlates strongly with the SI during shod (r=0.92) and barefoot (r=0.86) running (3). However, the SI is the usual gold standard for measuring strike pattern if the necessary laboratory equipment is available (i.e. three dimensional force platform and motion capture system) (41, 56, 67, 73).

Biomechanical studies have been conducted to assess risk factors for injuries and performance improvement during running with regards to footwear (67, 78), speed (26, 37), gender (26, 30), and other factors (e.g., surfaces, training modalities). In the last decade, media attention to the suggested benefits of barefoot running, including the adoption of MFS or FFS patterns, has prompted scientists to compare habitual strike patterns (4, 10, 56, 67) and study the effects of acute strike pattern modifications on running gait parameters (4, 10, 41, 42, 55, 56, 59, 73, 78).

Kinetic variables differ during imposed FFS compared to RFS. These differences include lower average and peak loading rate (56, 67, 78), greater joint axial contact forces at the knee and ankle joints (73), greater stiffness at the knee and lower stiffness at the ankle (41, 55), and lower or absent impact peak transient of the vertical ground reaction force (GRF) (25, 56, 59, 67). As there are definite biomechanical differences between strike patterns, understanding changes in lower extremity joint behaviors adopted to control shock transmission between strike patterns is of great importance to biomechanists (22).

1.2.2. Joint Stiffness in Running

Many biomechanical differences exist between strike patterns, but joint stiffness may be an important variable to explain the control of shock transmission within the lower extremity. Lower extremity joint stiffness may be an important variable related to risk of injury (4, 10, 25, 41, 42, 47, 48, 67). Stiffness in the human body, based on Hooke's law and the spring-mass model, is the quotient of the force required to deform an object and the angular displacement (5, 10, 41). The previous information assumes that the angular orientation of the object does not permanently change. Human body joint stiffness can be defined mathematically as:

$$k = \frac{\Delta M}{\Delta \theta}$$

Where k represents joint stiffness, $\Delta\theta$ represents the joint angle range of motion (ROM) from foot strike to the peak angle and ΔM is the change in the joint moment from foot strike to the peak moment. This is the most accepted mathematical methods for computing joint stiffness (76).

During the initial impact phase of running, a large shock wave is transmitted from the ground to the bottom of the foot. The body must then absorb a large amount of the shock from this impact by producing negative work through eccentric joint action. The knee joint produces the highest amount of negative work (i.e. time integral of angular power) during RFS running (22, 86, 89). During the propulsion phase, the body releases this stored energy through the hip, knee, and ankle joint extensors with the ankle producing the greatest amount of positive work of the three joints (89). The manner in which the body changes the location of shock transmission may influence injury risk and performance (22, 41, 78) which is in part modulated by changes in joint stiffness (41).

Increased lower limb and joint stiffness may also contribute to higher loading rates and peak GRF (10) which have been associated with retrospective injuries (56, 59, 60, 73, 85).

Some researchers have made the claim that acute changes in strike pattern will change likelihood of injury (41, 42, 55, 73, 78) and levels of performance due to changes in joint stiffness (41, 55). In RFS runners, the knee joint stiffness is reduced with an increase in ankle joint stiffness indicating greater shock absorption at the knee (41). Over time, this may result in an increased likelihood of injury due to transmission of shock to proximal joints and tissues and a decrease in performance due to muscular fatigue (22, 41, 55). As the opposite mechanical joint stiffness outcome occurs when a FFS is used (i.e. greater stiffness at the ankle compared to RFS), greater shock absorption will occur at the ankle suggesting greater plantarflexor muscle involvement (41). Reduced effectiveness of the eccentric action of the plantarflexors may occur with fatigue (41, 73). Over time, this could increase risk for acute plantarflexor injury at or around the ankle joint (73). The level of stiffness occurring in a limb and joint may also contribute to changes in performance (10, 32, 39, 53). Stiffness of the joints is dependent on multiple factors such as velocity (39, 53), surface stiffness (32), and foot strike pattern (4, 29, 41, 55). As running velocity increases, stiffness of the entire lower limb also increases which is usually modulated by increases in knee stiffness (40, 55) with little to no change in ankle joint stiffness (39, 53). In fact, well-trained distance runners exhibit this increase in lower limb stiffness with increased running speed (7). As the forces placed on the body increase with increasing velocity, an increased level of stiffness regulated by muscle action is necessary in order to control joint movement (10) and to optimize the efficiency of the stretch-shortening cycle (SSC) (7, 54). Thus, if increased stiffness of the lower limb may contribute to increased performance, an acute transition to FFS may be advantageous to RFS.

To date, studies have focused on the biomechanical differences between habitual and imposed strike patterns while runners are not fatigued. However, during long distance running, lower extremity joint muscles become fatigued due to the repetitive eccentric loading with each step (6). A gap in the literature exists to explain the interaction between imposed strike pattern and fatigue on lower extremity joint biomechanics and more specifically, joint stiffness.

1.2.3. Foot Strike and Fatigue during Running

Due to the repetitive nature of long-distance running, muscles fatigue and their ability to contract efficiently is affected (6). With reference to submaximal exercise such as endurance running, fatigue is defined as the inability to complete the work at the original intensity (2) which can affect lower extremity biomechanics (21, 61, 64). During running, lower extremity joint muscles are placed under repetitive SSC (52) because of eccentric action of joint extensors. Elastic energy is stored during this eccentric phase before the shortening (i.e. concentric) muscle action releases the stored energy (52). The resulting muscle damage following repetitive SSC are mostly due to the eccentric muscle action involved (24). Muscle damage may be a main contributor to fatigue, since significant increases in the blood markers creatine kinase and skeletal troponin I are observed following a marathon run (6). The increase in blood markers were concurrent with decreases in maximal isometric force, rate of force production of the plantarflexors, and decreased reflex sensitivity (measured via maximal M wave, H reflex, and stretch reflex tests). Together, these indicate that mechanical damage as well as reduced neural input to the muscle may contribute to fatigue (6). Lower extremity joint biomechanics are altered following downhill running, marathon running, and eccentric knee extensor damaging protocols (27, 68, 69). Muscle damage increases peak impact acceleration of the leg (21, 61), whole-body shock attenuation (i.e. relationship of head and tibial vertical acceleration) (21), and decreases ROM of the knee joint when delayed onset muscle soreness is present (27) (68). It is evident that muscle damage following long running bouts changes lower extremity joint biomechanics. To date, no research has studied the effects of fatigue following repetitive SSC (i.e. long distance running) on joint stiffness, specifically when considering foot strike patterns. As joint stiffness changes with differing strike patterns during running (41, 55) and has been associated with running injuries (42, 55), it is important to understand how joint stiffness changes with different strike patterns following a fatiguing run. In addition, due to the link between joint stiffness and the body's ability to control shock and dissipate energy, it is probable that changes in joint stiffness due to alterations in strike pattern could alter running economy.

1.2.4. Can Fatigue and Foot Strike Influence Running Economy?

An important variable to assess running performance and efficiency is running economy (RE): the "submaximal, steady-state rate of oxygen consumption" (17, 38) or VO_2 (17) at a set running speed. Greater running economy (i.e. lower oxygen cost at a given speed) usually indicates better running performances, as a runner will be able to sustain the set speed for a longer period of time (87). Running economy is dependent on lower extremity biomechanics, physiological variables, anthropometric measures, genetics, fatigue, and gender, among other factors (37, 45, 71, 87). Most of the biomechanical factors correlated with better running economy are also associated with RFS running (87). These variables include, among many others, higher stance phase maximum knee flexion (yielding a trend among groups however not statistically significant) (87), and greater extension of the knee joint at heel contact (37, 46, 87, 88). A larger peak knee flexion and a more extended knee at heel contact (i.e. variables associated with higher RE) would cause a reduction in sagittal knee joint stiffness if the change in extensor moment during stance remains constant. Thus, it would be expected that lower sagittal plane knee joint stiffness would be a contributing mechanical factor to increase RE during running. In fact, lower limb vertical stiffness is negatively correlated with RE (i.e. lower stiffness increases RE) while running at slower (3.35 m/s) (41) and faster (5.10 m/s) speeds (15).

Few studies have described the effects of alterations in strike patterns on changes in RE. Two studies have compared RE between *habitual* strike patterns (i.e. RFS and FFS) at different speeds and reported conflicting results (38, 66). In a 2014 study, RE was compared between 10 habitual RFS and 10 habitual FFS runners at different running speeds (3.0 m/s, 3.6 m/s, and 4.2 m/s) (66). This study found that RFS runners were more economical than FFS runners at the slow and medium speeds (66). Conversely, another study tested RE (i.e. VO_2 at set speeds) of habitual RFS (n=19) and habitual FFS (n=18) at different speeds (3.0 m/s, 3.5 m/s, and 4.0 m/s) and found no differences in RE between strike pattern groups at any speed (36). The average weekly mileage of these runners was 46.2 ± 27.4 km per week (36) while the average weekly mileage of previously mentioned study was 91 ± 24 km per week (66). Thus, the disparity in these findings may be related to the different running abilities or training volume of participants in both studies. Only one of these studies compared imposed strike patterns in both habitual RFS and FFS runners (36). At 3.0 m/s and 3.5 m/s, habitual RFS runners were more economical using a RFS compared to an imposed FFS pattern (between 5-9.3% greater RE in RFS (37, 66)). However, RE of habitual FFS runners was not different when using a FFS compared to an imposed RFS pattern across all speeds. Based on these findings, it appears that an imposed strike pattern (i.e. FFS) may have a greater effect on RE in habitual RFS. Neither of these studies, or other studies in the current literature, have assessed a potential interaction of fatigue and imposed strike pattern on RE. As fatigue is an important factor in long distance running, it is logical that its effects on running economy be studied.

Although greater running economy at a given speed may indicate better performance (17), it is important to understand what change in RE magnitude is meaningful to improve running performance. In a study comparing RE of elite distance runners at four submaximal speeds, a value of 2.4% change in RE was defined as meaningful (75). This value was obtained by calculating the degree of the smallest worthwhile change (adapted from Hopkin's smallest worthwhile effect (50)). A similar study comparing the RE at three submaximal speeds found that their protocol yielded no reliable measures to indicate a meaningful change in RE (77). The researchers in this study found that their incremental submaximal test was not a reliable measure of the smallest worthwhile change. The first study (75) tested elite male runners whereas the second study (77) tested recreational runners. Differences in homogeneity of groups may explain the difference in smallest worthwhile changes. This may also indicate that further research is needed to understand the reliability of certain testing protocols in order to obtain a meaningful difference in RE between specific groups.

1.2.5. Fatigue Quantification

As fatigue is related to changes in biomechanical, neurological, and physiological variables, it is difficult to quantify (2). Since a countermovement vertical jump (CMVJ) (34, 64) utilizes the SSC in lower extremity muscles, it has been used to assess fatigue following short sprinting bouts and longer sustained efforts (28, 34, 64). CMVJ height did not change before and after repeated and continuous high-speed bouts of 20 meter shuttle runs (Yo – Yo IR2) in athletes (34). Similarly, no difference was observed in CMVJ height before and after a marathon in a small number of highly trained runners (64). It appears that CMVJ height may not be an appropriate test measure to quantify fatigue following a long run.

Maximal isometric force has been shown to be a reliable method to quantify the level of fatigue induced by repetitive SSC activities such as running. Maximal isometric force of the plantarflexor muscles significantly decreased post marathon run (6) as well as the knee extensors using a similar protocol (64). Paschalis et al. (68) found that isometric peak torque decreases significantly after eccentric damage induced by six sets of maximal eccentric knee extensor contractions (68). As running involves multiple SSC (i.e. eccentric contractions), it seems logical that isometric force post long running bouts may provide a reliable measure to quantify fatigue.

1.3 Literature Gaps and Limitations

As a runner completes a long run, changes must occur in the joint kinetics and kinematics in order to ensure that the energy costs of running stay minimal as muscles become damaged and fatigued. The majority of scientific evidence describing joint kinetic, kinematic, and metabolic differences between strike patterns focuses on acute changes in non-fatigued states. Understanding these differences with relation to fatigue is paramount. As an acute transition in strike patterns is a popular topic in the scientific literature (56, 72), research on the effects of strike patterns following fatigue on lower limb biomechanics and running economy is warranted.

1.4 Research Questions and Hypotheses

Based on current literature findings and limitations, the following research questions and hypotheses were formulated:

Question 1: Does an imposed strike pattern affect ankle and knee joint stiffness before and after a long run in habitual RFS runners?

Hypothesis 1: Ankle joint stiffness was expected to be greater in RFS compared to imposed FFS before and after the long run.

Hypothesis 2: Knee joint stiffness was expected to be greater during imposed FFS compared to habitual RFS before the run but, similar between strike patterns after the long run.

Question 2: Does an imposed strike pattern affect RE before and after a long run in habitual RFS runners?

Hypothesis: RE will be greater during RFS compared to imposed FFS before the run but, similar between strike patterns after the run.

CHAPTER 2

The Effects of Imposed Foot Strike and Fatigue on Joint Stiffness and Metabolic Cost in Rearfoot Strike Runners

2.1 Introduction

In 2013, over 19 million people completed running races of between 5k to the marathon (i.e. 26.2 miles), a 295% increase since 1990 (1). The increased participation in running has also led to a higher number of injuries with between 20-80% of runners suffering a lower-extremity injury, most commonly at the knee (i.e. 8-50%) (82). Further, a greater number of injuries have been self-reported in runners who use a rearfoot strike (RFS; i.e. striking the ground first with the heel) (19, 81). With the resurgence of the popularity of barefoot running in the last decade, many scientists and barefoot running enthusiasts have suggested that mid-foot (MFS; striking the ground with the midfoot) or forefoot (FFS; striking the ground with the forefoot) strike patterns are less injurious than the commonly used RFS pattern. Approximately 75% of recreational and elite runners habitually use a RFS pattern (44). Thus, it is important to understand biomechanical differences between strike patterns to better substantiate anecdotal evidence for the positive effects of MFS or FFS on reducing injury risk in runners. For this reason, recent research has focused largely on differences in joint biomechanics following acute transitions in foot strike patterns during running (20, 36, 41, 73, 80, 84).

Joint kinetic differences exist between an acute transition to a forefoot strike (imposed FFS) and RFS in habitual RFS runners. When FFS is imposed in habitual RFS, lower loading rate of the vertical ground reaction force (GRF) (56, 67, 78), greater net axial joint contact force at the ankle (73), greater sagittal knee joint stiffness and lesser ankle stiffness (41, 55), and a lower or absent impact transient of the vertical GRF (25, 56, 59, 67) have been reported. A greater loading rate common during RFS compared to FFS running has been retrospectively associated with tibial stress fractures (56, 59, 70). As there are definite mechanical differences between strike patterns during running and joint stiffness is an indicator of the body's ability to control shock, understanding lower limb joint involvement in shock transmission between the strike patterns is of great importance to biomechanists, coaches, and runners (4, 10, 22). Not only do modifications in strike patterns yield different lower extremity joint biomechanics, they have also shown to yield different metabolic cost (37, 66).

An important variable to assess running performance and efficiency is running economy (RE): the submaximal oxygen consumption (VO_2) at a set running speed (17, 38). Better RE (i.e. lower oxygen cost at a given speed) usually indicates better running performances, as a runner can sustain a set speed for a longer period of time (87). RE is dependent on physiological variables, anthropometric measures, lower extremity biomechanics, genetics, fatigue, and gender, among other factors (37, 45, 71).

Most biomechanical factors that have been shown to correlate with greater RE are also associated with RFS running (37, 46, 87). For example, lower limb vertical stiffness has been negatively correlated with RE while running at slower (3.35 m/s) (45) and faster (5.10 m/s) speeds (15). Conflicting results exist in the literature regarding the effects of strike pattern on RE (37, 66). Since an imposed FFS in habitual RFS appears to reduce RE (37) and that RFS and FFS patterns yield different ankle and knee joint stiffness (41), joint stiffness may contribute to changes in RE.

During endurance running, it is thought that accumulated muscular fatigue will affect RE and lower extremity mechanics due to repetitive SSC and resulting muscle damage (27, 46, 46, 65, 68, 90). This fatigue may increase peak impact acceleration of the leg (21, 61), whole-body shock attenuation (i.e. relationship of head and tibial vertical acceleration) (21), and decrease knee ROM when delayed onset muscle soreness is present (27, 68). It is also established that an acute change in strike pattern from habitual RFS to imposed FFS alters running biomechanics (10, 39, 41, 53, 55, 73, 78, 80, 84) and to a lesser extent, RE (38, 66) during non-fatigued running. However, the effects of fatigue on biomechanical variables and RE between habitual and imposed strike patterns are still unknown.

Therefore, the primary purpose of this study was to understand the effects of an acute foot strike modification on ankle and knee joint stiffness before and after a fatiguing long run in habitual RFS runners. We hypothesized that ankle joint stiffness would be higher in RFS compared to imposed FFS. We also hypothesized that knee joint stiffness would be higher in imposed FFS compared to RFS before the run but that it would not be different between strike patterns after the run. A secondary purpose of the study was to compare RE between strike patterns before and after a long run. We hypothesized that RE would be greater during RFS compared to imposed FFS before the run but, similar between strike patterns after the run.

2.2 Methods

2.2.1 Subjects

Fifteen well-trained habitual RFS male distance runners were recruited for the study (Table 1). An *a priori* power analysis (G*Power 3.1.5) indicated that a total of 12 participants were needed to obtain a proposed Cohen's D effect size of 0.51, power of 0.8, and $\alpha < 0.05$ for repeated measures comparisons of fatigue assessment via peak knee extension moment after an exhaustive run (8). Subjects were included if they were free of any cardiovascular or metabolic disorders (e.g. hypertension, diabetes), free of any injuries for the previous three months and had no lower extremity surgeries in the previous 12 months. All participants were included if they ran an average of at least 30 miles per week for the past 3 months with one long run per week (i.e. at least 25% of weekly mileage) (18). This mileage criteria was used to replicate the typical mileage and training patterns of a runner training for a half or full marathon. Runners that changed their foot strike pattern in the 3 months before testing and/or currently running barefoot were excluded. Approval from the Institutional Review Board for Human Subjects Research at the University of Memphis was obtained and all subjects signed a written informed consent document prior to data collection.

Table 1. Body and training characteristics of participants and long run information during testing (*N* = 15)

	Mean ± SD
Age (yrs)	31.7 ± 9.3
Height (m)	1.80 ± 0.07
Body Mass (kg)	74.4 ± 11.5
BMI (kg/m^2)	23.0 ± 2.8
Mileage per Week (km)	75.9 ± 22.7
Long Run (mi)	19.0 ± 5.7
Long Run Duration (min)	90.4 ± 23.4
Long Run Pace (min/km)	4.9 ± 0.6
Treadmill Speed (m/s)	3.5 ± 0.4

Notes: BMI: body mass index

2.2.2. Procedures

During the first lab session subjects completed the consent form, health history and physical activity questionnaires and, an online survey to assess previous injury and training history. A 5-minute warm-up was completed followed by biomechanical assessment of strike pattern using the strike index (SI) (11) during over-ground running at the self-selected long run pace (Table 1). Subjects were included in the study if their SI value was below 33% (11). Following the strike pattern assessment, subjects completed practice trials of each lab test to be completed during the second laboratory session, which was completed at least 24 hours following the initial session. Subjects were asked to bring their own running shoes and clothes to the testing session and the same running shoes were used for all testing procedures. All laboratory tests were performed before and after the long run and the order of all laboratory tests is presented in Figure 1.

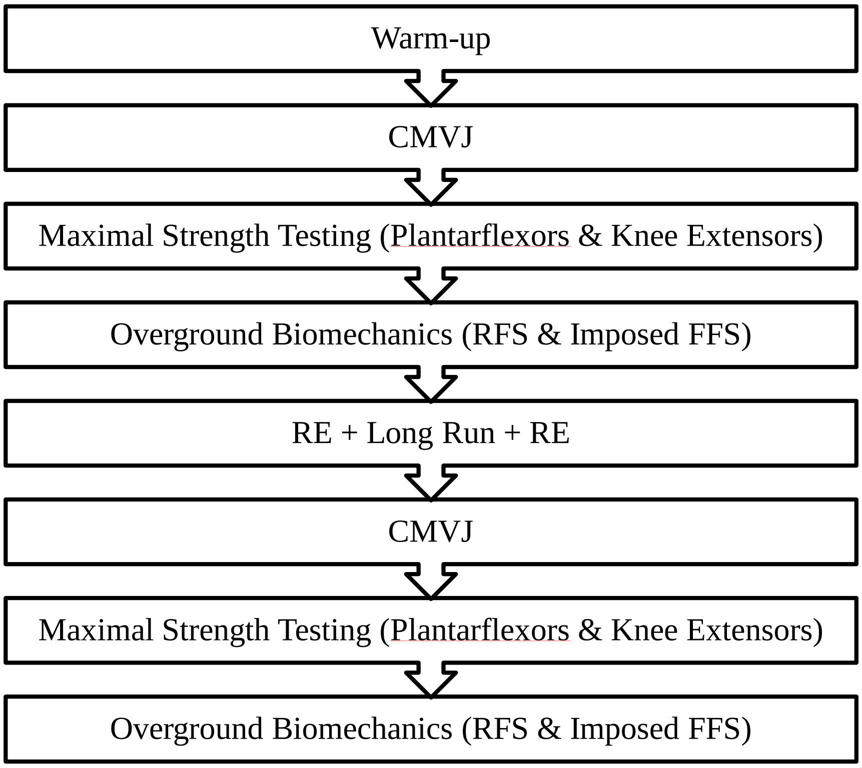

Figure 1. Flow chart illustrating order of events during the second lab visit.

Biomechanical Analyses

During the second laboratory session, a three-dimensional (3D) motion capture system (Qualysis, Gotenburg, Sweden) and a 3D force platform (AMTI, Watertown, MA) were used to collect lower limb kinematics and GRF, respectively. Before testing, subjects were asked to complete a five-minute warm-up run at a speed equivalent to their usual long run pace. Spherical reflective markers were placed on a number of anatomical landmarks including the iliac crests, greater trochanters, femoral epicondyles, malleoli, and head of the first and fifth metatarsals to define the pelvis, thigh, leg, and foot, respectively. Tracking markers were secured on neoprene wraps placed on the pelvis, thigh, and leg using a four-marker semi-rigid thermoplastic shell. A three-marker semi-rigid thermoplastic shell was secured over the heel cup of the shoe to track the foot. This model was used since the anatomical landmarks used to define segments are palpable through manual palpation (79). Anatomical marker locations were identified with a black ink marker during pre-run testing to ensure reliable marker placement before and after the long run. A one-second static calibration trial was recorded before the start of data collection to define joint centers and segment coordinate systems. Subjects then completed over-ground running trials on a 30m runway while contacting the force platform with their right foot. Five successful trials were completed using their habitual strike pattern (i.e. RFS) and imposed strike pattern (i.e. FFS) for a total of 10 trials. For the imposed FFS, subjects were instructed to allow the forefoot touch the ground first. No directions as to whether the heel was allowed to touch the ground after FFS instructions were provided. Practice trials were performed before each running condition to ensure proper strike pattern and running speed. A speed of ± 5% of their long run pace (calculated during the warm-up) was used and controlled during testing using an electronic timer (54035A, Lafayette Instruments Inc., IN, USA) and two infrared photo-cells (63501 IR, Lafayette Instruments Inc., IN, USA).

Running Economy Testing

RE was assessed using oxygen consumption (VO_2) during the first and last 15 minutes of the long run (Figure 1) at a set treadmill speed equivalent to their typical long run pace (Table 1). The long run was completed on a treadmill and expired gases were collected using a facemask and analyzed using a metabolic system (ParvoMedics TrueOne, Murray, Utah). Heart rate (HR) was monitored using a telemetry unit (Model H7 HR strap, Polar Electro, Lake Success, NY) strapped around the chest and communicating with the metabolic system to aid in assessment of steady-state. To warm-up, subjects ran for five minutes with the facemask on using their habitual strike pattern (i.e. RFS). At minute five, subjects were instructed to run at a randomly selected imposed FFS or RFS pattern. Expired gases were collected once steady-state (i.e. plateau of oxygen consumption and respiratory exchange ratio) was visually recognized. If steady-state was not achieved after five minutes, subjects continued to run until steady-state was reached. Subjects were then instructed to switch strike pattern at minute 10 where the same data collection procedures were conducted for another five minutes with the different strike pattern totaling 15 minutes of metabolic testing during the beginning of the long run. For the imposed FFS condition, participants were instructed to contact the ground with their forefoot first. During RE testing, strike pattern was visually monitored by the same researcher. After completion of RE testing using both strike patterns, subjects straddled the treadmill and the facemask was quickly removed before subjects continued their run using their habitual RFS pattern. RE testing was completed again during the last 15 minutes of the long run using the same procedures. Cadence (steps/min) was also measured at imposed FFS and RFS during RE measurements by counting the number of steps in one minute using a stopwatch.

Fatigue Protocol

The long run was used as a fatiguing protocol in the current study. The long run was equivalent to a distance of approximately 25% of each subject's average weekly mileage in the past 3 months (Table 1) (18) (i.e. weekly mileage of 40 miles equating to a 10 mile long run). The RE testing time at the start and end of the run (i.e. approximately 30 minutes) was included in the total run distance. The run was completed at the pace established during the warm-up, and subjects were not given any instructions regarding their strike pattern during the long run. Before, during, and following the long run, subjects were allowed to drink water *ad libitum*. However, they were not allowed to consume any calorie containing foods or beverages during the long run.

Quantification of Fatigue

Following a dynamic warm-up of 10 body-weight squats and 10 jump squats, the subject completed a countermovement vertical jump (CMVJ) three times with at least one minute rest between jumps. This warm-up was only completed before the pre fatigue CMVJ testing, as it was assumed that the subjects were sufficiently warmed-up from the long run when performing post fatigue CMVJ. Subjects performed as many practice attempts as needed to feel comfortable with the jumping test. Maximum vertical jump displacement was measured to the nearest 1.27 cm using a stand-alone Vertec jump trainer (Sports Imports, Hilliard, Ohio). Vertical displacement was defined as the jump height measured on the Vertec jump trainer after subtracting a one-hand reach height from a static, plantar-flexed position. The average jump height from the three trials pre and post fatigue was used in statistical analyses.

Immediately after the CMVJ tests, ankle plantarflexor (i.e. triceps surae and knee extensors (i.e. quadriceps) maximal isometric force was measured to compare muscular fatigue before and after the long run. For the plantarflexor strength test, subjects sat on a cushion mat over the floor with their back against a stable vertical surface. Their right knee was fully extended and their right ankle joint dorsiflexed at a 90 degree angle. The opposite leg was kept stationary to not aid in force application (Figure 2A). A force transducer (Model MLP-1K, Transducer Techniques, Temecula, CA) instrumented onto a metal chain was secured to an anchored vertical structure (i.e. the chair used for knee extensor strength testing). The end of the chain was attached to a leather cuff, which was wrapped around the right midfoot. For knee extensor strength testing, subjects were seated in a custom-made chair, and their right ankle was attached to a leather cuff and a force transducer instrumented onto a metal chain secured to base of the chair (Figure 2B). The knee joint angle was maintained at 90 degrees.

During muscle strength testing, subjects were instructed to push maximally against the cuff (i.e. the cuffs did not move) with concentric plantarflexor or knee extensor contractions on a verbal command for about 3 - 4 seconds, and then instructed to relax. The location of the cuff on the midfoot foot and ankle was kept constant to ensure consistent moment arm lengths of the force application before and after the long run using a black ink mark. Three trials for both joints were collected with a one-minute rest break between each trial for both joints. Data were collected at a sampling rate of 2000

Hz (Datapac 5, RUN Technologies, Mission Viejo, CA) and channeled through a 12-bit analog-to-digital converter (DAS1200Jr; Measurement Computing, Middleboro, MA).

Figure 2. A) Plantarflexor strength and B) knee extensor strength testing setup.

2.2.3. Data Analyses

Visual3D software (C-Motion, Inc., MD, USA) was used to compute all variables of interest. A right-hand rule with a Cardan rotational sequence (X-y-z) was used for the 3D angular computations where x represents the ML axis, y represents the AP axis and z represents the longitudinal axis. Kinematic data was interpolated using a least-squares fit of a 3rd order polynomial, with a three data point fitting and a maximum gap of 10 frames. Kinematic and GRF data were filtered using a fourth-order Butterworth low-pass filter at 8 and 40 Hz, respectively. A threshold of 10 N of the vertical GRF was used to detect both the start and end of the stance phase. Joint moments were normalized to body mass (Nm/kg). The ankle and knee joint angular kinematic and kinetic variables were expressed in the shank, thigh and pelvis coordinate systems, respectively. The pelvis was defined with the iliac crests and greater trochanters, and the hip joint centers were calculated at the location of one-quarter the distance between the ipsilateral and contralateral greater trochanters (83) Joint kinetic variables were computed using inverse dynamics and moments were reported as net internal moments. Primary dependent biomechanical variables included sagittal plane ankle and knee stiffness. Joint stiffness was computed using the following equation:

$$k = \frac{\Delta M}{\Delta \theta}$$

Where k represents joint stiffness (Nm/°), $\Delta\theta$ represents sagittal plane joint range of motion (ROM) from foot strike to the peak angle and, ΔM is the change in the absolute joint moment from foot strike to the peak moment (Nm). This is the most accepted of all mathematical methods for computing joint stiffness (76). Secondary mechanistic variables included sagittal plane knee and ankle joint ROM, peak knee extensor moment and ankle plantarflexor moment, and ankle and knee negative (i.e. first 50% of stance phase) angular work (i.e. last 50% of stance phase) as the time integral of angular power (J/kg). For all biomechanical variables, the average of all five trials was used in the statistical analyses.

Variables to quantify fatigue included CMVJ height (cm) and maximal isometric force during plantarflexion and knee extension. Maximal isometric force was calculated by averaging the force plateau defined as the time interval between the two instants when the rate of force development was zero. RE expressed as VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$) was collected during the last two minutes of the five-minute intervals for both strike patterns using the same speed at the start and end of the long run. Four 30-second average data points were extracted during this two-minute period and averaged together to be used in statistical analyses.

2.2.4. Statistical Analysis

A 2X2 within-within factorial (Foot Strike x Fatigue), repeated measures analysis of variance (RMANOVA) was used to evaluate biomechanical variables and RE. When necessary, paired t-tests were used for *post-hoc* pairwise comparisons. Paired t-tests were used to compare CMVJ height and plantarflexion and knee extension maximal isometric force pre and post fatigue. The alpha level was set at a significance level < 0.05 for all tests. Cohen's d effect sizes (ES) were calculated to assess effect magnitudes using the interpretation of Hopkins (49).

2.3 Results

2.3.1 Quantification of Fatigue

The Paired sample t-test showed no significant difference in CMVJ height (ES = 0.12) and maximal isometric plantar flexion force (ES = 0.16) between pre and post fatigue (Table 3). Maximal isometric knee extension force was significantly lower post compared to pre fatigue (p = 0.018; ES = 0.39) (Table 2).

Table 3. CMVJ and maximal isometric force pre and post fatigue (mean ± SD).).

Variables	**Pre**	**Post**	***P*-value**
CMVJ (cm)	35.0 ± 5.6	34.0± 7.1	0.36
Plantarflexor Strength (N)	500.7 ± 187.5	467.9 ± 223.0	0.29
Knee Extensor Strength (N)	388.6 ± 67.6	361.5 ± 76.5	**0.02**

*Note all bolded values indicate a significant difference (p < 0.05).

2.3.2 Joint Stiffness

For ankle stiffness, no significant interaction between foot strike and fatigue (*p* = 0.30) and no main effect of fatigue *(p* = 0.20) were found (Figure 3a; Table 3). A significant foot strike main effect was observed (ES = 1.47), with greater stiffness during RFS (12.1 ± 3.8Nm/°) compared to imposed FFS (7.7 ± 2.4Nm/°) (Figure 3a). For knee stiffness, no significant interaction between foot strike and fatigue (*p* = 0.24) and no main effect of fatigue (*p* = 0.41) were found (Figure 3b; Table 3). Similarly to the ankle, a significant foot strike main effect was observed (ES = 0.88), with greater stiffness during imposed FFS (8.9 ± 2.9Nm/°) compared to RFS (7.6 ± 2.5Nm/°) (Figure 3b). Note that knee stiffness values were based upon a sample size of 13 subjects rather than 15 due to equipment malfunction.

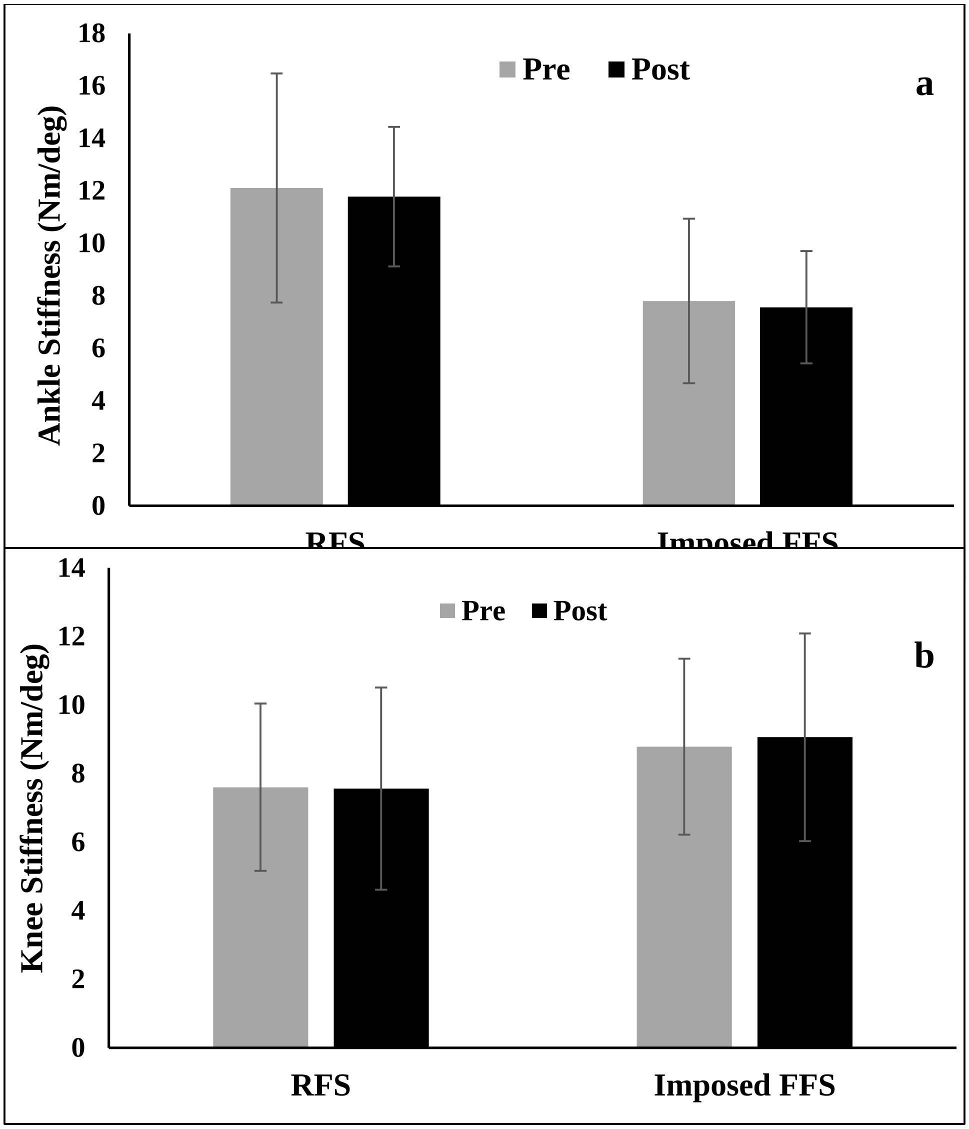

Figure 3: Mean (SD) of ankle (a) and knee (b) stiffness between strike patterns pre & post fatiguing run.

Table 3. Kinetic and kinematic ankle and knee joint variables during RFS and imposed FFS pre and post fatigue (mean ± SD).

	Pre		**Post**		***P*-values**		
Variables	**RFS**	**Imposed FFS**	**RFS**	**Imposed FFS**	**Foot Strike**	**Fatigue**	**Inter.**
Ankle Stiffness (Nm/°)	12.4± 4.4	7.8 ± 2.7	11.8 ± 3.1	7.6 ± 2.1	**<0.001**	0.20	0.30
Knee Stiffness (Nm/°)	7.6 ± 2.4	8.8 ± 3.0	7.6 ± 2.6	9.1 ± 3.0	**<0.001**	0.41	0.25
Ankle ROM (°)	19.2 ± 3.1	32.6 ± 6.2	19.4 ± 2.8	32.1 ± 5.6	**<0.001**	0.53	0.81
Knee ROM (°)	30.2 ± 4.5	29.7 ± 4.2	27.5 ± 4.9	24.6 ± 4.6	**<0.001**	**0.04**	0.05
Peak Ankle Moment (Nm/kg)	-2.7 ± 0.4	-3.1 ± 0.5	-2.6 ± 0.4	-3.1 ± 0.4	**<0.001**	0.19	0.44
Peak Knee Moment (Nm/kg)	2.6 ± 0.7	2.4 ± 0.7	2.5 ± 0.7	2.3 ± 0.4	**0.016**	0.32	0.40
Cadence (steps/min)	170.9 ± 11.0	173.1 ± 9.9	172.6 ± 10.0	173.4 ± 9.9	**0.043**	0.35	0.06

*Note all bolded values indicate statistically significant effects ($p < 0.05$).

2.3.3 Secondary Kinetic and Kinematic Variables

There were no significant interactions between foot strike and fatigue for ankle ROM, knee ROM, ankle negative work, knee negative work, peak ankle moment, peak knee moment, and cadence ($p > 0.05$) (Table 3). A significant main effect of foot strike on ankle joint ROM was observed (ES = 2.89), with a larger ROM during imposed FFS (19.3 ± 3.0°) compared to RFS (32.3 ± 5.9°). A trend toward a statistically significant foot strike X fatigue interaction in knee joint ROM was observed ($p = 0.05$). A significant main effect of foot strike on knee ROM was also observed (ES = 0.89) with larger knee ROM during RFS (29.9±4.4°) compared to imposed FFS (26.0±4.7°). A significant fatigue main effect for knee ROM was observed (ES = 0.39) with larger knee ROM pre (28.8±4.7°) compared to post fatigue (27.1±4.4°).

A significant foot strike main effect was also observed for peak ankle plantarflexor moment (ES = 1.11) with a greater moment observed during imposed FFS (-3.1 ± 0.5Nm) compared to RFS (-2.6 ± 0.4Nm). A small, significant main effect of foot strike on peak knee extensor moment was observed (ES = 0.33) with RFS yielding a greater moment (2.6 ± 0.7Nm) compared to imposed FFS (2.4 ± 0.6Nm). Cadence during the treadmill run showed a small but significant main effect (ES = 0.16) of foot strike with higher cadence observed during imposed FFS (173.7 ± 9.9 steps per minute) compared to RFS (171.7 ± 10.5 steps per minute).

2.3.4 Running Economy

There was no significant interaction between foot strike and fatigue on RE ($p = 0.68$) (Figure 4; Table 3). A significant main effect of foot strike was observed for RE (ES = 0.38), with lower RE during imposed FFS ($37.5 \pm 5.9 \text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) compared to

RFS (35.5 ± 5.3 ml·kg^{-1}·min^{-1}). A significant main effect of fatigue was also observed on RE (ES = 0.24) with lower RE post (37.2 ± 5.7ml·kg^{-1}·min^{-1}) compared to pre fatigue (35.8 ± 5.5ml·kg^{-1}·min^{-1}). Data from only 13 subjects were used due to malfunction of the metabolic system.

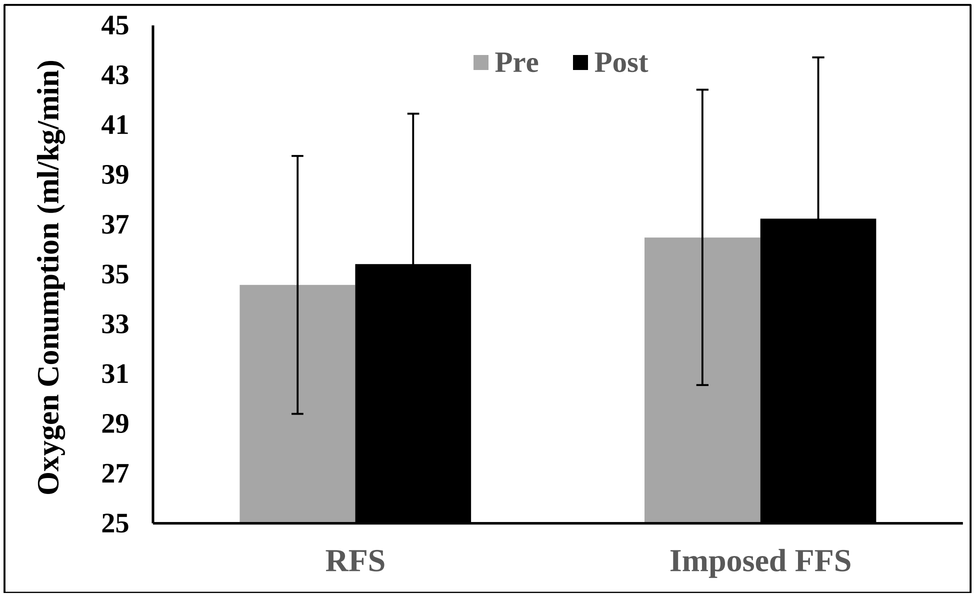

Figure 4: Mean (SD) of running economy pre and post fatigue and between rearfoot (RFS) and imposed forefoot (imposed FFS) patterns

2.4 Discussion

Since joint stiffness is different between foot strike patterns during running (41) and this change may be related to injury development, this study aimed to understand the effects of an acute foot strike modification on ankle and knee joint stiffness before and after a fatiguing long run in habitual RFS runners. In addition, due to importance of high running economy for performance in long distance running, we also aimed to compare running economy between strike patterns before and after a long run.

Our first primary hypothesis was supported, as ankle joint stiffness was greater during RFS compared to imposed FFS before and after the run. The large effect size for ankle stiffness (ES = 1.47) indicates a meaningful difference for ankle joint stiffness between habitual RFS and imposed FFS. These findings are consistent with previous literature (41). During RFS, the joint ROM is smaller than in imposed FFS (Table 3). This provides a mechanistic explanation for the higher ankle joint stiffness in RFS as the joint ROM is the denominator of the joint stiffness equation (i.e. $\Delta M/\Delta\theta$). As expected, fatigue did not change the difference in ankle joint stiffness between RFS and imposed FFS. The unchanged difference in ankle stiffness before and after the run is not only explained by the unchanged ankle dorsiflexion ROM but may also be explained by the unchanged maximal isometric plantarflexion force following the run. A reduced ankle joint stiffness would have been expected if the plantarflexors had been drastically fatigued (i.e. reduced plantarflexion force following the run). In addition, since ankle stiffness is computed using both the change in plantarflexor moment and dorsiflexion ROM, the results suggest that although peak ankle moment was significantly higher in imposed FFS (Table 3), the change in plantarflexor moment was not different before and after fatigue. However, since the peak plantarflexor moment is often used as one of the input variables in musculoskeletal simulations to estimate net axial ankle force (23, 73), it may suggest higher net contact ankle force during imposed FFS compared to RFS (73). Habitual RFS runners should exercise caution when acutely adopting a FFS pattern as higher plantarflexors involvement and potentially larger net ankle axial contact forces could be injurious (73). However, it is still currently unclear whether larger contact forces can lead to increase bone stresses and injury development. The finding of increased peak plantarflexor moment during imposed FFS in habitual RFS is consistent with previous running literature (73, 80) but our findings suggest that fatigue-state does not alter sagittal plane ankle biomechanics differently between strike patterns in habitual RFS runners.

Our second primary hypothesis was partially supported as knee joint stiffness was greater during RFS compared to imposed FFS before the run but contrary to our hypothesis, this difference remained following the run. The moderately larger knee stiffness during imposed FFS compared to habitual RFS (ES = 0.88) is consistent with previous literature (41). Similar to ankle stiffness, the difference in knee joint stiffness between strike patterns was also independent of fatigue. The greater knee joint stiffness is explained by the smaller knee flexion ROM during imposed FFS compared to RFS since joint ROM is the denominator in the joint stiffness equation (i.e. $\Delta M/\Delta\theta$). Since cadence was increased while speed was controlled, we assumed that step length was reduced during imposed FFS compared to RFS. In fact, Gruber et al. (36) have reported higher stride frequency (i.e. cadence) along with shorter step length during imposed FFS in habitual RFS runners. It is important to note that since the effect size in cadence between strike patterns was small, it may suggest that other more important factors contributed to the reduction in knee flexion ROM.

Although fatigue did not affect knee joint stiffness, knee flexion ROM was generally smaller after fatigue with a moderate effect size (ES = 0.88). Considering the difference in joint stiffness between strike patterns before the long run remained following the run, we assumed that the change in knee joint moment was reduced with similar magnitude as knee flexion ROM. The reduction in knee flexion ROM may be confirmed by significant reduction in maximal isometric knee extension force following fatigue. As knee extensors become damaged or fatigued, they may not be able to efficiently control eccentric knee joint flexion as the stance limb is loaded. Indeed, peak knee flexion during running is reduced following knee extensor muscle damage elicited by numerous repetitions of isokinetic eccentric contractions (68). Further, this reduction in knee flexion angle during running is concurrent with higher knee stiffness when muscle soreness is present (27). Thus, although knee flexion ROM was reduced in the current study, the lack of change in knee stiffness from fatigue was not surprising since our runners did not experience any immediate muscle soreness following the run. It is possible that longer runs (e.g., marathon or ultra-marathon) will elicit immediate muscle soreness that could reduce knee joint stiffness following fatigue.

Our secondary hypothesis was also partially supported, as RE was improved during RFS compared to imposed FFS before the run. The results were contrary to our hypothesis as RE improvements in RFS remained following the long run. The small effect size (ES = 0.24) for the difference in RE could suggest lack of meaningfulness. However, we observed a decrease in RE of 5.3% in RFS independent of fatigue. We also observed a 3.8% decrease in RE across fatigue states independent of strike pattern. These values are greater than the 2.4% change reported in the literature (75) which is indicated a meaningful difference between the means of the foot strike main effect and the means of the fatigue main effect, respectively. The effect sizes as interpreted by the Hopkin's scale (50) for foot strike and fatigue main effects in our study were small (ES = 0.38 & ES = 0.24, respectively). However, based on the interpretation from Saunders et al. (75), our findings suggest that the strike pattern and fatigue effects on RE may be meaningful. These findings support those of Gruber et al. (36) who noted that a habitual RFS pattern yields higher RE than imposed FFS at slow (3.0 m/s) and medium (3.5 m/s) running speeds. The difference in RE between strike patterns may be related to knee joint stiffness. Knee joint stiffness is a large factor responsible for modulating leg stiffness (40, 55). Since lower leg stiffness is associated with lower RE (16), the higher knee joint stiffness during imposed FFS compared to RFS may partly explain the lower RE. Further, the lower RE during imposed FFS may be the result of a novel task for habitual RFS runners. Our study shows that, in general, habitual RFS runners may not benefit metabolically (i.e. greater RE) from an acute change in strike pattern as they fatigue.

This study has a number of limitations that must be addressed. Firstly, frontal and transverse plane joint biomechanics and hip biomechanics were not analyzed in the current study. It is possible that changes in these planes of motion may be relevant to injury risk and performance when comparing strike patterns before and after fatigue. Further, only men were included in our study and since there are known biomechanical difference between genders during running (31, 57), the findings may not be generalizable to female runners. Also, since our runners only showed moderate reductions in knee extension force following the run, more intense long runs (e.g., race simulation) or even longer runs may be needed to increase fatigue and show greater changes in biomechanical and metabolic variables. A muscle force test to failure may have been more appropriate to assess fatigue as this would be more indicative of the type of fatigue induced during long running bouts. However, a maximal test (i.e. short time to completion) was designed as we aimed to reduce the amount of testing time immediately following the long run. Lastly, the current study only assessed acute modifications in strike pattern in habitual RFS, and chronic effects of strike pattern modifications with respect to fatigue remain unknown. However, these limitations do not reduce the implications of our findings as studies assessing the effects of long fatiguing runs on lower limb stiffness are lacking in the literature.

2.5. Conclusion

Findings from this study show that imposed FFS in habitual RFS yielded lower ankle joint stiffness, greater knee joint stiffness and lower running economy. However, these different between strike patterns were independent of fatigue. Overall these findings indicate that an acute transition to an imposed FFS may not mechanically or metabolically benefit RFS runners regardless of fatigue state. Coaches may instruct runners to “get on your toes” at the end of the race in the attempt to increase speed or RE. The results of this study indicate that, especially in a fatigued-state at the end of longer running bouts, this may not be beneficial.

CHAPTER 3

GENERAL RECOMMENDATIONS

3.1. Summary

Findings from this study show that imposed FFS in habitual RFS yielded lower ankle joint stiffness, greater knee joint stiffness and lower running economy. However, these different between strike patterns were independent of fatigue. Overall, these findings indicate that an acute transition to an imposed FFS may not mechanically or metabolically benefit RFS runners regardless of fatigue state.

3.2. Recommendations for Future Research

Findings from the current study have summoned new research questions for our lab. It is well documented that certain lower limb biomechanics differ in females (i.e. decrease peak knee flexion, increased hip internal rotation, etc.) (31, 57). Since the current study included only male runners, future research should aim to identify potential gender differences when runners become fatigued and how strike pattern modifications with regards to joint stiffness and running economy. Fatigue may also alter specific variables that have been retrospectively associated with injury development (e.g., loading rate, ipsilateral trunk lean, internal hip rotation, eversion velocity) and thus, to further understand the effects of fatigue on risk of injury development, these variables should be studied within this research design. As our study yielded a small effect on knee extensor strength (ES = 0.39), future research may increase the intensity or volume of the long run to assess greater changes in joint mechanics and running economy. Since we only studied well-trained runners, future studies should also assess biomechanical and metabolic differences before and after fatiguing runs in novice runners. Finally, as most runners are advised to follow a gradual transition from a RFS to imposed FFS, training studies should be conducted to assess the effects of chronic strike pattern transitions on relevant biomechanical and metabolic variables before and after fatigue.

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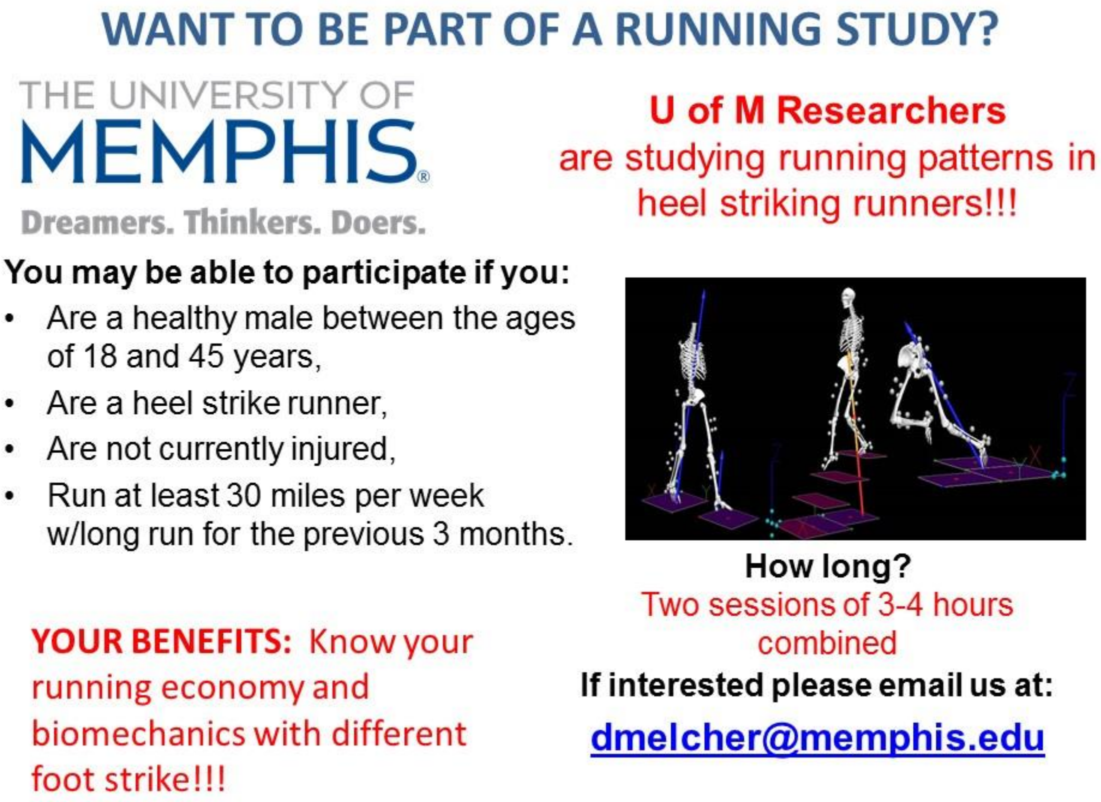
APPENDIX A



WANT TO BE PART OF A RUNNING STUDY?

THE UNIVERSITY OF
MEMPHIS
Dreamers. Thinkers. Doers.

U of M Researchers
are studying running patterns in heel striking runners!!!

You may be able to participate if you:

- Are a healthy male between the ages of 18 and 45 years,
- Are a heel strike runner,
- Are not currently injured,
- Run at least 30 miles per week w/long run for the previous 3 months.

How long?
Two sessions of 3-4 hours combined

YOUR BENEFITS: Know your running economy and biomechanics with different foot strike!!!

If interested please email us at:
dmelcher@memphis.edu

Institutional Review Board
315 Administration Bldg.
Memphis, TN 38152-3370
Office: 901.678.3074
Fax: 901.678.2199

APPENDIX B
IRB #: #3512
Expiration Date: 11/21/2015

Consent to Participate in a Research Study

The change in difference of lower limb joint biomechanics and metabolic cost between foot strike patterns after fatigue

1 WHY ARE YOU BEING INVITED TO TAKE PART IN THIS RESEARCH?

You are being invited to take part in a research study about running motion and metabolic cost with relation to fatigue and foot strike patterns. You are being invited to take part in this research study because you are a male, rear foot striking runner and have been running at least 30 miles per week for the previous 3 months including one long run per week. If you volunteer to take part in this study, you will be one of about 20 people to do so at the University of Memphis.

2 WHO IS DOING THE STUDY?

The person in charge of this study is Daniel Melcher, a Graduate Research Assistant in the Health and Sport Sciences department at the University of Memphis. There may be other individuals such as graduate students on the research team assisting at different times during the study.

3 WHAT IS THE PURPOSE OF THIS STUDY?

By doing this study, we hope to learn what running variables may be related to specific running-related performance and injury prevention.

ARE THERE REASONS WHY YOU SHOULD NOT TAKE PART IN THIS STUDY?

We will be recruiting healthy, young men between the ages of 18- 45 years that have been running at least 30 miles per week for the previous three months, have no current lower limb injuries, do not currently run barefoot, and have not had any lower extremity surgeries in the previous 12 months. If you do not fit the previous criteria, then we apologize, but you cannot participate in the study.

4 WHERE IS THE STUDY GOING TO TAKE PLACE AND HOW LONG WILL IT LAST?

The research procedures will be conducted in the Musculoskeletal Dynamics laboratory (Fieldhouse 171) at The University of Memphis. You will need to come to the Elma

Roane Field House, Room 171 for one testing session of approximately 3-4 hours in length.

5 WHAT WILL YOU BE ASKED TO DO?

During the laboratory visit you will be informed of all procedures, potential risks, and benefits associated with the study through both verbal and written form.

Testing

All testing will take place at the University of Memphis Musculoskeletal Dynamics Lab – FH171

DAY 1 (~30minutes)

During the first lab visit, you will asked to complete the informed consent form (Appendix C), health history, and physical activity questionnaires. Your height and weight will be measured. A survey to assess your previous injury history will also be completed before any testing. Your foot strike type will be assessed visually during this session during a treadmill run (~10 minutes).

You will be asked to bring running shoes, running shorts, socks, short sleeve t-shirt, water bottle, and a towel to this lab visit. The same running shoes will be used for all testing procedures. You may be asked to run without a shirt to ensure proper capture of the reflective markers. In addition, during the first lab visit you will be given time to become familiar with all testing procedures. Verbal instructions on how to adopt a FFS will also be given during the treadmill run and you will be allowed to practice this new (imposed) running style.

DAY 2 (~3 hours)

At least 24 hours following the first laboratory visit, you will be asked to attend a second testing session during day 2.

You are asked to bring the same running shoes used in **DAY 1,** running shorts, socks, short sleeve t-shirt, a water bottle, and a towel to this lab visit. The same running shoes will be used for all testing procedures. You may be asked to run without a shirt to ensure proper capture of the reflective markers.

<u>Test 1 – Motion capture analysis</u>

You will be asked to complete a 5 minute warmup run at a self-selected controlled “long run” pace on a treadmill at zero degrees of incline (i.e. – level surface). This pace will be recorded and used for all other testing protocols. Then, a three-dimensional (3D) motion capture system (Qualysis, Sweden) and 3D force platform (AMTI, Watertown, MA) will be used to track your lower limb and joint motion as well as ground reaction forces while running. Reflective markers (12.5mm plastic spheres covered in reflective tape) will be placed on specific anatomical locations to track hip, knee, ankle, and foot motion. The information collected with the motion capture system does not produce video images of the subjects. Instead, it provides positional data (i.e., numbers relative to an origin) of each marker during movement tasks. Therefore, you cannot be identified from this data. To ensure reliability of marker placement between testing days, washable ink will be used to mark the location of reflective markers. You will be instructed to run down a 30m runway while striking your right foot on the force platform. Five successful trials using your habitual foot strike (heel strike) will be completed. Following those five trials, five more trials at your non-habitual foot strike (forefoot) will be completed. A speed of ±5% of your long run pace (calculated during the warmup) will be used. Speed will be calculated using an electronic timing system with infrared photo-cells.

Test 2 – Countermovement Vertical Jump Trials

You will be asked to complete a countermovement vertical jump (CMVJ). You will be allowed to practice the movement by placing both feet on the force platform and performing the CMVJ with use of swinging your arms. Three successful trials of the CMVJ will be completed. Maximum height as well as force-related data will be collected via Qualysis Track Manager (Qualysis, Sweden) software.

Test 3 – Ankle and Knee Muscle Strength

Ankle plantarflexor (i.e., calves) and knee extensors (i.e., quadriceps) strength will be performed to compare muscular fatigue before and after the fatiguing protocol which may provide mechanical explanations for our primary dependent variables. For the plantarflexor strength test, you will sit on a thin cushion mat over the floor with your back against a stable vertical surface. Your right knee will be fully extended outwards and right ankle joint maintained at a 90 deg angle. A force transducer instrumented onto a metal chain will be secured to the vertical stable surface. The end of the chain will be attached to a cloth cuff which will be wrapped around the right forefoot. You will be instructed to push maximally with the right foot against the cuff (the cuff does not move) on a verbal command for about 3-4 seconds, and will then be instructed to relax. For the knee extensor strength test, you will be seated in a chair with the right ankle attached to a cuff and a force transducer instrumented onto a metal chain secured to the vertical stable surface. You will then be instructed to push maximally against the cuff (the cuff does not move) on a verbal command for about 3-4 seconds, and will then be instructed to relax. Three trials for both joints will be collected with a minute rest break between each contraction of both joints. The data will be collected using the Biopac software.

Test 4 – Running economy testing (pre-fatigue)

A ParvoMedics TrueOne Metabolic System (Murray, Utah) will be used to collect metabolic data. The data (gas exchanges: oxygen and carbon dioxide) will be collected with a rubber mask secured over your nose and mouth. You will then be allowed to run for ten minutes at the previously selected pace using your habitual foot strike (i.e., RFS) and an imposed FFS on the same treadmill used to warm up (total of 20minutes of data collection). Metabolic cost data (oxygen consumption) will be collected during the last five minutes of the ten minute periods after you have reached a steady-state metabolic and heart rate. This is measured through minute ventilation (VO_2) and respiratory exchange ratio (RER) using the metabolic system. For the FFS condition, you will be instructed to allow the forefoot to contact the ground first, allowing the heel to touch the ground. Heel-strike is defined by allowing the rearfoot to contact the ground first. After completion of the non-habitual foot strike protocol, the mask used to collect metabolic data will then be safely removed after completely ceasing movement on the treadmill.

Fatiguing Running Protocol

Directly following the initial running economy testing, you will complete a long run on the laboratory treadmill equating to a distance of approximately 25% of their weekly mileage (e.g. – 25% of 40 total miles/week equals a 10 mile long run). This is an accepted percentage of weekly mileage used for a long, aerobic run for individuals training for long distance running events. The run will be completed at the pace established during warmup and you will be instructed to use your habitual foot strike pattern. With 20 minutes left in the long run, researchers will ask you to stop the treadmill in order to place the metabolic system on the subject. The same metabolic testing will be completed as described in Test 4 above during the last 20 minutes of the fatiguing protocol.

Upon completion of the long run and metabolic testing, tests 2, 3 and 1 will be completed in that order to mirror the test order before the fatiguing protocol.

WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS?

The potential risks and discomforts that may be experienced are minimal. You may experience soreness from the running tests. Considering the sub-maximal effort involved and your running experience, it is unexpected that you will experience any soreness following the running tests.

WILL YOU BENEFIT FROM TAKING PART IN THIS STUDY?

There is no guarantee that you will get any benefit from taking part in this study. However, you will receive information regarding metabolic cost and knee biomechanics for differing foot strikes before and after a fatiguing run. The results from this study may provide beneficial information to the running community regarding the association of foot motion with and running performance.

DO YOU HAVE TO TAKE PART IN THE STUDY?

If you decide to take part in the study, it should be because you really want to volunteer. You will not lose any benefits or rights you would normally have if you choose not to volunteer. You can stop at any time during the study and still keep the benefits and rights you had before volunteering. If you decide not to take part in this study, your decision will have no effect on the quality of care, services, etc., you receive from the University. As a student, if you decide not to take part in this study, your choice will have no effect on you academic status or grade in the class.

IF YOU DON'T WANT TO TAKE PART IN THE STUDY, ARE THERE OTHER CHOICES?

If you do not want to be in the study, it is solely up to you but there are no other choices except not to take part in the study. If you choose to not take part in the study, there are no other options to gain the benefits of the study.

WHAT WILL IT COST YOU TO PARTICIPATE?

There are no costs associated with taking part in the study except for your full commitment to the timeframe of the study.

WILL YOU RECEIVE ANY REWARDS FOR TAKING PART IN THIS STUDY?

Participation in the study is voluntary and you will not receive payment to participate.

WHO WILL SEE THE INFORMATION THAT YOU GIVE?

We will make every effort to keep private all research records that identify you to the extent allowed by law.

Your information will be combined with information from other people taking part in the study. When we write about the study to share it with other researchers, we will write about the combined information we have gathered. You will not be personally identified in these written materials. We may publish the results of this study; however, we will keep your name and other identifying information private. The information on the forms we will have you fill out will remain private, and only the study staff will see them.

We will make every effort to prevent anyone who is not on the research team from knowing that you gave us information, or what that information is. After the forms you will fill out are completed, they will be kept in a locked file cabinet at which my research team will be the only ones to be able to access it. Any information that gets transferred electronically will be stored on a computer with passcode entry that only the research team will know.

We will keep private all research records that identify you to the extent allowed by law. However, there are some circumstances in which we may have to show your information to other people. If any medical situation arises at which the paramedics or any other form of emergency care have to be called, we may be required to provide health history forms and or contact information. For example, the law may require us to show your information to a court or to tell authorities if you report information that could pose a danger to yourself or someone else. Also, we may be required to show information which identifies you to people who need to be sure we have done the research correctly; these would be people from such organizations as the University of Memphis or any other funding agencies that may have ties with our research study.

CAN YOUR TAKING PART IN THE STUDY END EARLY?

If you decide to take part in the study you still have the right to decide at any time that you no longer want to continue. You will not be treated differently if you decide to stop taking part in the study.

The individuals conducting the study may need to withdraw you from the study. This may occur if you are not able to follow the directions they give you or if they find that your being in the study is more risk than benefit to you. The consequences of withdrawing would include the lack of any personal benefits/gains you may have experienced by taking part in the study. Your withdrawal would result in the power of the study to go down, and may require the researchers to find a replacement subject if the time permits.

ARE YOU PARTICIPATING OR CAN YOU PARTICIPATE IN ANOTHER RESEARCH STUDY AT THE SAME TIME AS PARTICIPATING IN THIS ONE?

You may take part in this study if you are currently involved in another research study as long as you fit the inclusion/exclusion requirements. As long as the current study you are participating in doesn’t require you to perform strenuous exercise that may change the way that you normally run, then you should be able to partake in multiple studies, once discussed with the researcher. It is important to let the investigator/your doctor know if you are in another research study. You should also discuss with the investigator before you agree to participate in another research study while you are enrolled in this study.

WHAT HAPPENS IF YOU GET HURT OR SICK DURING THE STUDY?

If you believe you are hurt or if you get sick because of something that is due to the study, you should call Daniel Melcher at (440)265-9387 immediately. If it is an emergency that requires medical attention, please dial 911.

If any abnormal signs or symptoms are present during your participation, testing will be terminated and you will receive attention, following the Adverse Events plan of the Human Performance Laboratories. Otherwise, no treatment will be provided.

It is important for you to understand that the University of Memphis does not have funds set aside to pay for the cost of any care or treatment that might be necessary because you get hurt or sick while taking part in this study. Also, the University of Memphis will not pay for any wages you may lose if you are harmed by this study.

Medical costs that result from research related harm cannot be included as regular medical costs. Therefore, the medical costs related to your care and treatment because of research related harm will be your responsibility.

A co-payment/deductible from you may be required by your insurer or Medicare/Medicaid even if your insurer or Medicare/Medicaid has agreed to pay the costs. The amount of this co-payment/deductible may be substantial.

You do not give up your legal rights by signing this form.

WHAT IF YOU HAVE QUESTIONS, SUGGESTIONS, CONCERNS, OR COMPLAINTS?

Before you decide whether to accept this invitation to take part in the study, please ask any questions that might come to mind now. Later, if you have questions, suggestions, concerns, or complaints about the study, you can contact the investigator, Daniel Melcher at (440)265-9387 or dmelcher@memphis.edu, his advisor Dr. Max Paquette at mrpqette@memphis.edu, or come by the researcher's office located in FH 135. If you have any questions about your rights as a volunteer in this research, contact the Institutional Review Board staff at the University of Memphis at 901-678-3074. We will give you a signed copy of this consent form to take with you.

WHAT IF NEW INFORMATION IS LEARNED DURING THE STUDY THAT MIGHT AFFECT YOUR DECISION TO PARTICIPATE?

If the researcher learns of new information in regards to this study, and it might change your willingness to stay in this study, the information will be provided to you. You may be asked to sign a new informed consent form if the information is provided to you after you have joined the study.

___________________________________ __________
Signature of person agreeing to take part in the study Date

____

Printed name of person agreeing to take part in the study

___________________________________ __________

Name of [authorized] person obtaining informed consent Date

APPENDIX C

The University of Memphis Institutional Review Board, FWA00006815, has reviewed and approved your submission in accordance with all applicable statuses and regulations as well as ethical principles.

PI NAME: Daniel Melcher
CO-PI:
PROJECT TITLE: The effects of fatigue on ankle and knee joint stiffness and metabolic cost between foot strike patterns
FACULTY ADVISOR NAME (if applicable): Maxime Paquette

IRB ID: #3512
APPROVAL DATE: 11/21/2014
EXPIRATION DATE: 11/21/2015
LEVEL OF REVIEW: Expedited

Please Note: Modifications do not extend the expiration of the original approval

Approval of this project is given with the following obligations:

1. If this IRB approval has an expiration date, an approved renewal must be in effect to continue the project prior to that date. If approval is not obtained, the human consent form(s) and recruiting material(s) are no longer valid and any research activities involving human subjects must stop.

2. When the project is finished or terminated, a completion form must be completed and sent to the board.

3. No change may be made in the approved protocol without prior board approval, whether the approved protocol was reviewed at the Exempt, Expedited or Full Board level.

4. Exempt approval are considered to have no expiration date and no further review is necessary unless the protocol needs modification.

Approval of this project is given with the following special obligations:

Thank you,

James P. Whelan, Ph.D.

Institutional Review Board Chair

The University of Memphis.