THE EFFECTS OF LOCALIZED MUSCULAR FATIGUE ON LOWER BODY RUNNING MECHANICS

A THESIS

SUBMITTED TO THE GRADUATE SCHOOL

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE

MASTER OF SCIENCE

BY

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MUNCIE, INDIANA

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COMMITTEE APPROVAL:

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Declaration

The work in this thesis is, to the best of my knowledge and belief, original, except when acknowledged in text. This material has not been submitted either in whole or in part for a degree at this or any other university

Samuel Rosario Date

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Abstract

THESIS: The Effects of Localized Muscular Fatigue on Lower Body Running Mechanics

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Background: Running is a popular form of exercise and inherent to many sports. Running while fatigued has been associated with decrements in performance and increased risk of acute and overuse running injuries. However, the relative contributions to running mechanics from individual muscle(s) have not been clearly established and could help further elucidate risk factors and anatomical structure foci during training. This study's purpose was to analyze alterations in kinematic, kinetic, and ground reaction force (GRF) variables with the onset of localized fatigue. It was hypothesized that knee flexor and extensor fatigue on separate occasions would increase impact forces, joint angles, joint moments, and powers compared to pre-fatigue values.

Methods: Five healthy college-aged adults (2 males, 3 females: 23.60 +/- 1.14 years; 1.71 +/- 0.13m; 67.60 +/- 14.50kg) ran at 3.61m/s prior to and following isokinetic knee flexion and extension (concentric and eccentric) efforts for a total of three, two-minute runs. Motion capture and force data were used to calculate joint motion and loading throughout each run. Data were analyzed using RM-ANOVA evaluating kinematic and kinetic changes following fatigue of knee flexors and extensors for each run.

Results: Maximum braking force significantly increased from immediate post-fatigue to two-minutes post-fatigue ($p=0.003$; $\eta^2_p=0.677$). Peak vertical GRF significantly ($p<0.05$) decreased

from pre-fatigue (2.79 +/-0.09BW) to immediate post-fatigue (2.46+/-0.10BW) of the quadriceps. Propulsive knee power significantly ($p<0.05$) decreased from pre-fatigue (11.32+/-1.74Nm/kg) to immediately post-fatigue (6.93+/-0.90Nm/kg) of the quadriceps. Knee abduction moments were significantly higher ($p=0.001$; $\eta^2_p=0.960$) for running measures following hamstring fatigue over that of quadriceps fatigue.

Discussion: Quadriceps fatigue showed the greatest pre-fatigue to immediately post-fatigue changes. Vertical impact peak force and propulsive knee power decreased significantly more immediately post- quadriceps fatigue than hamstring fatigue. Horizontal braking forces exhibited similar changes for both muscles over time, having significantly increased during the fatigued run.

Chapter 1: Introduction

Running for exercise is a popular choice for many people. In the US, from 2009-2015, 8.6% of people aged 15 and older (approximately 17 million people) reported running for physical activity (Bureau of Labor Statistics, 2015). However, running is notorious for its relationship to lower body injuries. Injuries per 1000 hours of running have been reported to range from as little as 2.5 injuries in long-distance track and field athletes, to as high as 33.0 injuries in novice runners (1). Novice runners are impacted by injuries at rates considerably higher than their recreational running peers (33 vs. 7.7 injuries per 1000 hours of running) (1). One factor that has been shown to contribute to the risk of injury associated with running is the change in mechanics due to the onset of muscular fatigue (2–5). The effect of fatigue in runners can include factors such as decreased knee stability, decreased leg stiffness, decreased energy transfer within the muscle tendon unit, and decreased lumbo-pelvic control (6). All levels of running have some degree of inherent risk of injury to the runner. However, the lowest proportion of injuries seem to occur in moderate duration and intensity categories of running like jogging, while sprinting and ultra-marathon running have been shown to result in the greatest proportion of injuries of runners (7). Based on the findings from previous research it has been suggested that stress induced by either running speed or duration were indicators for increased risk of injury (1,5–10). Compensations in running mechanics caused by the influence of local muscle fatigue can include changes in joint angles and ground impact forces, change in muscle activation patterns, and overall decrements in running performance, which could be indicators for an increased risk of injury.

Fatigue is generally defined as a decrease in the capacity of voluntary muscle force production (11–13). Muscular fatigue can be divided into two different protocol types based on where the fatigue is induced or experienced: (1) whole-body fatigue, and (2) localized fatigue. Whole-body fatigue, or generalized fatigue, is a more widely researched topic that encapsulates fatigue of the entire body from physical exertion. This fatigue method was reported to result in decreased voluntary muscular force production, changes to movement patterns, decreased motor control and overall impairment in task performance (9,10). Localized muscle fatigue is generally limited to fatigue of a single muscle, or muscle group, acting about a particular joint of interest. Similar to whole-body fatigue, localized fatigue also involves decreased capacity of voluntary muscle force production, changes to movement patterns, and decrements to motor control and task performance (2–4,14). The notable difference between these two types of fatigue is the extent to which the overall neuromuscular system has been fatigued. One benefit of analyzing running mechanics using localized muscular fatigue is the ability to observe the changes at specific joints or muscle(s) that occur between pre- to post-fatigue performance. Isolating fatigue to an individual joint or muscle can provide insight into how task performance is influenced by fatigue, and further understanding into potential injury risk factors caused by altered mechanics at the fatigued joint and the surrounding non-fatigued joints.

Assessing the influence of fatigue on running has often involved utilizing a whole-body fatigue protocol through assessing changes following long-distance running (i.e., marathon or ultramarathon running) (1,5,7,15). Muscular performance changes observed following a marathon run using electromyographic (EMG) activity revealed a 26 +/- 14% decrease in maximal isometric peak torque of the knee extensors, and significant decreases in integrated EMG (iEMG) of the hamstring muscles post-race (15). During treadmill running to fatigue, joint ROM has been shown to significantly increase at the hip and knee, as well as cause decreased joint stiffness and significantly reduce vertical displacement of the center of gravity (COG) (5).

Using a more acute form of whole-body fatigue, researchers assessed overground sprinting to fatigue and reported significant declines in eccentric and concentric knee flexor strength (16). Significant reductions in eccentric biceps femoris (BF) myoelectrical activity were also reported following sprinting induced fatigue (16). The importance of the activation patterns of the BF pertain to their higher incidence of injury during sprinting (16,17). One potential reason for the higher injury rates may be related to the elevated contraction load placed on the hamstring muscles during the swing phase of sprinting (18,19). Taken together, the effects of fatigue on running mechanics and muscle activation patterns are clearly influenced by running induced whole-body fatigue (5,15,16). However, exploring specific regions of the body, and through isolating fatigue to specific regions, additional insight may provide justification of more specific reasons for running related injuries through altered mechanics. Further, by understanding the role played by specific muscles and joints, researchers may gain additional clarification regarding compensations resulting from different levels of fatigue or musculoskeletal injury that may modify the overall movement pattern.

Localized fatigue research focused on fatiguing a group of muscles, or a singular muscle, has been assessed through either volitional contractions or facilitated by using electromyostimulation (EMS). EMS may elicit greater recruitment of muscle fibers, but the activation of motor units is significantly different than that achieved through voluntary contractions, where the level of alternating motor unit activity in the motoneuron pool is not the same (20). That is to say, fatigue caused by EMS compared to voluntary contractions may not accurately represent the fatigue achieved during physical activity. However, by utilizing EMS to induce muscular fatigue, researchers were able to isolate fatigue to a single quadriceps muscle (i.e., vastus lateralis) which resulted in significant reductions in overall knee extension force, but also resulted in acute increases in synergistic muscle activity allowing subjects to still complete the knee extension task (21). In a similar study, after EMS induced fatigue of the soleus, significant reductions in voluntary muscle activity were revealed during plantarflexion, but not accompanied by a significant change in maximal force output (14). It was suggested that the biarticular gastrocnemii had compensated sufficiently during plantarflexion, to sustain optimal force output during the maximal voluntary contraction (MVC) between pre- and post-fatigue measurements (14). These findings suggest that when fatigue is induced in a single muscle the ability to produce force may be able to be compensated by greater recruitment of muscle synergists. While this electrically induced isolated muscle fatigue provides some interesting insights into the control of muscle force production, the excitation of the muscle via EMS bypasses the alpha motor neuron by directly stimulating the muscle transcutaneously rather than depending on the CNS to be the origin of the muscle stimulation (22,23). Thus, EMS can be seen as an artificial activation of the muscles, omitting the need for the CNS to be involved in the process, and is not entirely representative of volitional muscle fatigue. To this end, it is less clear how the isolated fatigue of individual muscles or muscle groups can influence of the control of motor tasks, especially multi-joint movements such as overground gait.

One benefit of utilizing localized muscle fatigue is that while changes may occur at the isolated joint, the capabilities of the surrounding joints are not impaired and may provide insight into the compensations that may occur during fatigue or injury. For example, fatigue of the invertor muscle group of the ankle via isokinetic fatigue has been found to impair dorsiflexion, and also cause increased impact force upon initial contact while running (4). Similar research involving ankle joint fatigue confirms a tendency for decreased dorsiflexion at impact, and increased muscular activation of the vastus medialis (VM) and gastrocnemius (GAS) during running (3). Moving proximally from the ankle, fatigue about the knee joint has been linked to other distinct compensatory strategies. Following isokinetic knee joint fatigue, researchers reported increased knee flexion at impact along with increased knee joint excursion, resulting in decreased knee joint stiffness (2,3). The researchers further suggested that increased quadriceps muscle activation was a key indicator of fatigue, and the body's response to compensate for the loss in strength. By increasing knee flexion at impact the quadriceps may be placed in a more effective joint angle to facilitate force production while fatigued (2). Further, through the increase in knee flexion there may be an attenuation of the impact ground reaction force (GRF), in addition to a slightly longer period of ground contact to maintain the necessary force impulse, while reducing the magnitude of the peak impact force needing to be absorbed by the body (24). Interestingly, the combined effect of knee flexor and extensor fatigue was not shown to significantly alter hamstring to quadriceps coactivation ratios upon ground impact, but did increase preactivation from pre- to post-fatigue (2). Based on increased pre-activation observed following fatigue, fatiguing the hamstring and quadriceps muscles independently could result in decreased force output in either muscle group, and may create instability about the knee. Examining compensations that occur at joints both proximal and distal to the fatigued muscle and joint may provide further insight into the overall role, and potential impairments occurring as a result of isolated muscular fatigue.

Impaired running economy is generally determined by decreased joint moments and powers, implying increased stress about a joint, and detriments to propulsive or absorptive power. Marathon running as a prime example of the onset of fatigue, primarily influencing knee extension torque (15). The repeated eccentric muscle action demanded by running activity has been shown to debilitate muscular force production capacity (25). It is possible that as a runner becomes more fatigued, resisting weight acceptance will manifest via increase absorptive power at the knee, and decreased propulsive power at the knee to allow the body to continue moving optimally through space. These prospective increases in joint loading post-fatigue may cause these changes as reports of the greatest magnitudes of net torques, powers and work were at the hip and knee in the sagittal-plane (26). Decrements in optimal joint motion under the loads placed on the body, especially with the onset of fatigue, may result in considerable deviations in joint torques and power that ultimately hinder running performance.

In addition to assessing the nature of the location of the fatigue (whole-body vs. localized) it is also important to consider the overall type of fatigue that is incurred and the concomitant changes in performance that could result from either central or peripheral fatigue. Central fatigue involves a loss of central mechanisms associated with the central nervous system (CNS), that ultimately results in an inability to perform voluntary muscle contractions (10,23). Alternatively, peripheral fatigue consists of changes to internal mechanisms that can lead to muscle failure (11,27–30). Differentiating the origin of fatigue between central and peripheral mechanisms provides insight into why muscular activity changes may have occurred and how the response differs between the two. Central fatigue has been suggested to provide a protective mechanism preventing further progression towards muscle failure (23), which may decrease risk for injury. By inhibiting communication from the CNS to the muscles, a loss of central command (7,22,27–29), central fatigue can act as a performance limiter prior to peripheral muscle failure (23).

Compensatory strategies to maintain task performance after local muscle fatigue has been reported in various studies, where adaptive strategies were found with other muscles increasing activation to support a loss of force after fatigue (2,3,21,34,35). A more specific example is from

Kellis and colleagues (2011) who reported notable changes after fatigue of the knee flexors and extensors, describing how an antagonist inhibition strategy arose, increasing the effort made by the quadriceps, and influencing the joint stability of the knee during loading-response. These results suggest that the location of fatigue can alter movement patterns as a compensatory mechanism to maintain force production. It is possible that there could be substantial changes in movement caused by fatigue, as synergists play their supportive roles to sustain the integrity of the system.

Muscle composition (e.g., type I, type IIa & b) has been shown to directly affect the body's response to fatigue. Individuals with a greater proportion of type I fibers (i.e., endurance athletes) versus type II fibers (i.e., strength trained athletes) has been shown to result in a delayed onset of fatigue for the former group based on a difference in recruitment patterns (36,37). The difference in recruitment patterns traces back to changes in motor neuron discharge rates and conduction velocities, where a reduced discharge rate indicates the onset of fatigue (37). When observing changes in muscle activation characteristics by muscle type, the principle of recruitment order would suggest the initial recruitment of less fatigable type I fibers, and if the force requirements are low, the stimulation of type II fibers is mitigated. With the onset of muscular fatigue however, integrated EMG (iEMG) was shown to increase corresponding with increased excitation of the motoneuron pool (27,31). Perhaps increased activity of muscle fibers capable of greater force output (e.g., high-threshold motor units) because of fatigue of lower threshold motor units is a risk of injury in itself during dynamic movements.

The influence fatigue has regarding muscle length changes throughout the duration of multi-joint movements has been observed in multiple studies (18,25,38–41). Muscle length changes in running is of particular interest since running is a cyclic movement, composed of repeated concentric and eccentric muscle actions inherent to sustain motion. The repeated eccentric loading that occurs stride after stride increases damage to the muscles (23,38,42), and concentric contractions cause greater energy expenditure via greater motor unit discharge rates (36,42), with a combination of the two having a potentially detrimental effect on task performance. The hamstrings tend to act eccentrically during stance and concentrically during swing (42). Some studies have reported greater injury risk to the hamstrings during late swing and late stance due to peak musculotendon force and negative work observed (18,43). The eccentric activity of the quadriceps to counteract increasing knee flexion is standard (42), and quadriceps muscular activity has been shown to increase in response to muscular fatigue as the knee flexes with greater ROM during loading response (2,3). Repeated concentric and eccentric contractions of the muscles puts substantial strain on them. This repetitive motion is a very demanding task, and the onset of fatigue can considerably alter the efficiency and performance of these muscle actions while running. Decrements in muscle function throughout the running cycle can have a considerably negative impact on running mechanics and increase the risk of injury in runners throughout the duration of activity.

Using iEMG, tracking the change, and degree of change of motor drive is possible by normalizing activation levels to either maximal voluntary contractions or to standardized movements to determine the level of muscle excitation achieved during other activities (11). By establishing a baseline level of muscle activation during standardized movements, the activation levels observed during submaximal and repetitive contractions (e.g., running) can provide insight into the changes in motor unit recruitment and firing rates. With the onset of fatigue, excitation frequency tends to decrease, which is associated with decrements in force output, and its effects vary depending on individual differences in muscle contractile speed (11,44). The excitation rate can be contrasted across different activities and pre- and post-fatigue to assess changes in motor unit activation, which may result in changes in coordination and intensity of muscle activation during functional tasks like locomotion.

Research Questions & Hypotheses

Isolated muscle fatigue research has incorporated several different methods to evaluate its effect on running performance (2–4). Previous studies that incorporated a localized fatigue protocol about a particular joint (e.g., ankle, knee) have assessed the compensations that occurred as a result of fatiguing both the flexor and extensor muscles simultaneously and only in one leg. However, research has not investigated the effects of localized muscular fatigue of the flexor or extensor muscles separately, or in both legs on running performance. By isolating fatigue to just the flexors or extensors at a single joint additional insight may be gained to determine the specific role, and potential limitations and impairments resulting from reduced function in single muscle groups. The insight provided by assessing these changes may also help to provide support for injury mechanisms resulting from impaired function as a result of fatigue or injury. Therefore, the purpose of this study was to compare how fatigue of the quadriceps, or fatigue of the hamstrings, influenced muscular activity, kinematics, and kinetics of treadmill running. More specifically, the goal of this study was to address the following research questions: (a) How does localized fatigue effect pre- to post-fatigue lower body running kinematics during the running cycle? It was hypothesized that fatigue of the quadriceps would cause greater knee and hip flexion during the stance phase, and increased knee flexion during the swing phase. Additionally, it was hypothesized hamstring fatigue would cause decreased knee flexion in the swing phase, and at initial ground contact; (b) How does localized fatigue effect pre- to post-fatigue running kinetics, such as impact and braking forces at initial contact, and joint moments and powers during the swing and stance phases? It was hypothesized that peak impact and braking forces will increase from pre- to post-fatigue after quadriceps fatigue, but not hamstring fatigue. Additionally, it was hypothesized that hip and knee joint moments will increase during the stance phase, but powers will decrease.

Chapter 2: Review of Literature

Running is a common form of exercise that often imposes risk of injury across all areas of experience. In the US, the Bureau of Labor Statistics reported from 2009-2015 that 8.6% of people aged 15 and older reported running for physical activity (Bureau of Labor Statistics, 2015). That is roughly 17.0 million people in the US of varying experience levels who reported running for physical activity. Running has also been associated with injuries in individuals who run recreationally, to those who run in competition. In a previous report, per 1000 hours of running, novice runners experience 33.0 injuries, recreational runners experience 7.7 injuries, and in the lowest reports long-distance track and field runners experience 2.5 injuries per 1000 hours running (1). After observing participants for time-loss injuries caused by running over a year-long period, 84.9% of novice runners reported time-loss injuries with cross-country runners as high as 77.4%, long-distance road runners 43.4%, and 31.3% for marathon runners (7). Clearly running injuries are present amongst a variety of populations, but the cause for injuries sustained is not clear. The risk factors for running injuries have been reported to range from duration of running activity (7), experience level (1), poor training practices, footwear, and issues with strength and flexibility (45). These risk factors may seem to be straight forward and easily accommodating for assisting with injury prevention measures, but the influence muscular fatigue has on injury risk factors while running adds additional details that aren’t accounted for in the injury risk assessments done in previous studies. Fatigue is generally defined as a decrease in the capacity of voluntary muscle force production available in the muscles (11–13). As such, fatigue can have a debilitating effect on the body during exercise, and its influence on running performance is especially of interest for the purpose of injury prevention and analysis of its effect on running mechanics.

The role of fatigue in injury risk is multifactorial, but it is generally understood that there is a decrease in performance upon fatigue's onset. Previous research has pointed to fatigue's influence on energy absorption in rabbit digitorum longus, reporting between 69.7%-92% energy absorbed after electrically stimulated fatigue compared to controls in the contralateral limb (46). Energy absorption was calculated as the area under the length-tension deformation curve, which was found to be influenced the greatest in the early portion where the muscle was being stretched. The importance of energy storage is especially clear in the return of elastic energy under eccentric contractions while under the influence of fatigue, as the return of energy becomes increasingly impaired as fatigue becomes more severe. Additionally, biarticular muscles like the rectus femoris, hamstrings, and gastrocnemius are at greater risk for stretch-induced injuries.

Whole-Body Fatigue vs. Localized Fatigue

The fatigue protocol of choice for research is important and depends on the specific aim(s) of the research. The aim of whole-body fatigue compared to localized fatigue have essentially the same goal, but different approaches. Whole-body fatigue is self-explanatory in that the fatigue that is experienced, or is sought after in protocol, is throughout the entire body. The body is put through a fatigue protocol that attempts to exhaust subjects in order to examine how the body reacts to stimuli, or how performance is changed when compared to testing pre-fatigue. Typically, research conducting whole-body fatigue protocols seek to observe the physiological changes that occur, such as changes in heart rate, blood lactate, maximal aerobic capacity (VO_2), and other factors that may be influenced. However, there is a fundamental issue with whole-body fatigue and biomechanical analysis. Although kinematics, kinetics, and electromyographic (EMG) data can be observed after whole-body fatigue, it is difficult to locate and analyze the changes that occur, considering the lack of a specific area of the body that can be attributed to the changes that may have risen.

Localized fatigue involves isolating fatigue to specific location, and observing what compensations may occur, and how they may contribute to decrements to performance, or to injury risk during activity. This method of localizing fatigue to a known location can provide a clear insight into kinematic, kinetic, EMG, and motor control changes that can contribute to the decrements to performance and risk of injury.

Effect of Whole-body Fatigue on Running Mechanics

Despite the lack of specificity that whole-body fatigue provides in analyzing changes in mechanics, a brief comparison of what kind of changes occur when compared to local fatigue can be useful. This being that there are many similarities in the results of whole-body and localized fatigue research but portioning out parts of the body is where the specific cause of change can be identified. Many of the most common whole-body fatigue studies related to running involve long-distance running to exhaustion like marathon running, and sprinting to fatigue, either using a treadmill or running overground.

Marathon running is a classic test of endurance and high physical demand on the body, and one of the best tests for fatigue’s effects on the body after running overground. A group of experienced endurance runners were tested for the effects of fatigue after marathon running and found a 26 +/- 14% decrease in maximal isometric peak torque in the left knee extensors. Additionally, a significant decrease in the maximal integrated EMG activity of the vastus medialis and vastus lateralis was observed by 36+/- 26% and 42 +/- 25%, respectively (15). Nicol et al. (2007) reported considerably reduced maximal voluntary force production, despite six of the seven subjects exhibiting higher levels of neural activation to the muscles. This suggests there was such great wear of the contractile mechanisms, the corresponding decrease in the neural input to the muscles could not evoke further increases in voluntary contraction.

Treadmill running affords better control of factors that can influence the reliability and validity of data collection, and close observation of things like joint range of motion (ROM), GRF, and muscular activity in a lab setting (47,48). Whole-body fatigue induced by treadmill running has been shown not to significantly affect GRF, but significantly increase ground contact time, as well as knee and hip joint ROM at later periods of running duration. Furthermore, decreased stiffness of the knee and ankle joints over the duration of run time, and changes in the vertical displacement of the center of gravity (COG) (5). The Incremental maximal Exercise Test (IMET) has also been observed to cause degradation of gait stability and increased gait variability (9). However, the changes in gait stability and variability were not significant enough to interrupt movement efficacy and were proposed to be compensated for by the motor system in order to maintain adequate coordination.

Maximal-effort sprinting, and running at increasing speeds to induce fatigue has previously been reported to create increased stress on the muscles of the lower body as well (16). Repeat sprint running has been found to significantly decline concentric and eccentric knee flexor strength, by 10 and 15%, respectively, and more considerably in the BF than other muscles observed (16). The decrease in eccentric knee flexor strength was explained to be due to considerable decreases in the BF EMG activity in addition to the onset of fatigue of the lower body. This finding is important in that it emphasizes greater loss of muscular force production, explained by EMG activity differences after the fatigue protocol, suggesting a greater implication for injury in the BF muscle. This kind of change in muscular activity may also be further explained by the onset of fatigue toward the end of a maximal-effort sprint, considering reports of greater activation of muscles with fatigue as a compensatory mechanism to maintain joint coordination patterns (8).

Whole-body fatigue has proven to show there are changes that can be observed by precisely measuring kinematic, kinetic, EMG, and coordination changes. But the influence fatigue has on the body still can be broken down further. Of the most commonly studied variables on the effects of fatigue on spatiotemporal gait parameters, it was found that the changes were mostly dependent on the muscles that were fatigued, and the muscles in the legs were affected the greatest when compared to postural muscle fatigue studies (49).

Effect of Localized Fatigue on Running Mechanics

Ankle Joint Fatigue

It is clear that whole-body fatigue has a considerable impact on running mechanics, yet the cause for those changes is what cannot be easily accounted for. As previously examined, whole-body fatigue research has shown decrements in performance compared to the pre-fatigued state. Considering there to be negative influences of fatigue on the body, breaking down the influence localized muscular fatigue has about certain joints within a multi-joint movement should afford deeper analysis. Thus far, whole-body fatigue has been shown to influence joint ROM, changes in muscle activation patterns, coordination, joint stiffness, and other factors, keeping in mind this is a non-exhaustive list. It should, then, be expected that localized fatigue will produce similar results and more.

Kinematic differences can be expected with fatigue about different joints. Fatiguing the dorsiflexors tends to create a decrease in dorsiflexion angle at heel strike impact (3,4). This decrease in dorsiflexion at impact may be the cause for increased rate of the peak impact force, and additional fatigue of the invertors significantly influences the rate of decline of impact forces, but impact magnitudes tend not to be affected (4). A further perspective to add onto ankle muscle fatigue from research by Stutzig et al. (2015), with respect to the plantar flexor muscles (soleus and gastrocnemius (lateralis and medialis)). Fatiguing these three muscles individually does not result in different outcomes concerning the different synergistic muscles that compensate for the muscles that are fatigued. Results from this study further reported that fatigue of either the soleus or biarticular gastrocnemius could compensate for one another, with minimal change in force compensations amongst the corresponding synergistic muscles. These findings raise an interesting point that, although localized muscular fatigue has occurred, expectations of changes in performance may not always follow as synergistic muscles may compensate for the loss in muscular force enough to continue the task normally.

Knee Joint Fatigue

Knee joint fatigue research, when focusing on running, commonly involves fatigue of the flexors and extensors of the knee (quadriceps and hamstrings, respectively), fatigue simultaneously or independently, and either by voluntary muscular contraction, or electrical muscle stimulation. A similar finding between whole-body fatigue and knee joint fatigue is the tendency for increased flexion at the knee during initial contact (IC), or upon impact with the ground (2,3,5). Considering this tendency for increased knee flexion has not previously been linked to fatigue at the ankle joint, further analysis concerning which aspect of knee joint fatigue may be causing this can be justified. Simultaneous fatigue of the flexors and extensors of the knee causes an increase in quadriceps muscle activation upon impact, which is termed the quadriceps-dominant strategy (2). In order to counteract the increased knee flexion, the quadriceps muscle, acting as the agonist for knee flexion, must act eccentrically to extend the knee so that the leg does not collapse into further flexion while being supported on one leg (2). The antagonist muscle to the quadriceps is the hamstrings, which also coactivates concentrically to create stability about the knee (50). This symbiotic relationship of hamstring and quadriceps coactivation maintains the integrity of the joint, and a ratio of muscular activation between these two muscles acts as an indicator of the quantity of joint stiffness about the knee (2,50). A combination of greater knee flexion and an increased hamstring to quadriceps coactivation ratio shows there is a decrease in knee joint stiffness, since the increased quadriceps muscle activation implies a force generating compensation due to fatigue (2). Observing the potential decrements in joint stiffness about the knee after fatigue, measured by the coactivation ratio between the quadriceps and hamstrings, may be a positive indicator of injury risk to the muscles acting at the knee joint while running.

Another method of muscular fatigue, though less common, is using neuromuscular electrical stimulation (NMES). NMES is useful because it allows researchers to target muscles more specifically by placing electrodes on a local muscle or muscle group, and also allows researchers the ability to modulate muscular contraction force (51). Because voluntary muscle contraction declines with greater onset of fatigue, EMS can enhance muscular stimulation beyond the common person’s capacity for voluntary muscular contraction (51). Local fatigue of the vastus lateralis (VL) using NMES has been shown to still result in completion of knee extension exercise, but greater muscular activation of the remaining quadriceps muscles (vastus medialis (VM), vastus intermedius, rectus femoris (RF)) are what compensate in the loss in force from the VL (21). Looking back at Stutzig et al. (2015), fatigue of the individual muscles in the calf resulted in compensations from synergistic muscles that kept task performance consistent. So, perhaps hyper focused fatigue of specific muscles is not as beneficial for investigative purposes as it is to observe the compensations that occur after fatigue of a cluster of muscles like the quadriceps and hamstrings. And what’s more, stimulation of human muscle does not transfer over entirely compared to voluntary muscle contraction, like what occurs in situ while running.

Causes and Indicators of Muscular Fatigue

Although it’s previously been noted that there is a difference between whole-muscle and localized fatigue in terms of the purpose both serve for research, their similarities in the causes and locations of fatigue need to be further explored. The locations and cause for failure are commonly considered to fall under task dependency, central nervous system (CNS) failures, inhibitions in transmission from the CNS to muscles, and internal mechanisms of individual muscle fibers (11,44). And a further distinction needs to be made with the difference between central and peripheral fatigue. Central fatigue relates more closely to whole-body fatigue because it refers to physiological mechanisms linked with the (CNS), and how these processes are organized with the onset of fatigue, while peripheral fatigue relates more generally to localized fatigue because it involves changes in motor unit characteristics, as well as the mechanical and cellular process changes that occur (10,11). An important caveat is that central and peripheral fatigue are not mutually exclusive with respect to whole-body or localized fatigue, as the two types of fatigue work in conjunction with one another in a complex harmony that is not well understood. Because the specifics of each type of fatigue are beyond the scope of this literature review, examples of fatigue protocols where both types occur in the literature will be included, and brief explanations of related material on central and peripheral fatigue will be discussed in the following sections.

Central Fatigue and Task Dependency

Before examining specific processes like intracellular mechanisms and neuromuscular changes, mechanical parameters of fatigue are of primary concern. The task performed when observing muscular fatigue can also be predictive of how the muscles will be influenced, with factors like the intensity and duration of activity, and contraction type (concentric, isometric, eccentric) that may dominate portions of the fatigue protocol (10). This may seem obvious at a surface level, but the prior mechanisms leading to fatigue will vary by fatigue protocol. For example, lower intensity activity requires fewer motor units to be activated, and higher intensity activity requiring greater force output subsequently requires more motor unit activation. And with increased force comes a progressive demand for recruitment, generally in order of increasing motor unit size (52). Task dependency is important, but also complicated because although arranging a fatigue protocol to impair certain physiological processes is possible, not every mechanism contributes to performance limitations, and this varies depending on the specifics of the task (10,44).

Central Fatigue and Loss of Central Command

One of the main indicators of the onset of central fatigue is a lack of central command from the motor cortex, as well as other suprasegmental centers, that inhibits voluntary muscle contraction to be sustained (10). For example, localized fatigue of the VL via NMES results in an increased central command to the quadriceps by compensating the loss in force with its synergists (21). If fatigue and decreased force production is localized to only one location, the VL in this instance, and not to the entire muscle group, the CNS will vary the activation of the surrounding muscles to potentially generate the amount of torque required to complete the task (10). This neuromuscular strategy has been further demonstrated by a sustained knee extension at

5% maximal voluntary contraction (MVC) over a one hour period, where EMG recordings indicated a variation in muscular activity among the individual muscles in the quadriceps to maintain adequate torque generation for the entire contraction duration (53).

It appears that neural activation of the muscles with only purely voluntary muscle contraction is well below submaximal (23). Therefore, a loss in voluntary muscle contraction without the use of interpolated twitch, an electrical impulse applied in addition to a MVC (13), can indicate whether central fatigue has occurred. If there is a greater MVC via electrical stimulation than there is via voluntary contraction, a central component of fatigue can be inferred. However, an interpolated twitch that does not result in a greater muscular contraction is due to peripheral fatigue, causing complete failure of the muscle to produce additional force.

Peripheral Fatigue

As central fatigue is to loss of voluntary muscle force output from CNS failure and reduced central command to muscles, peripheral fatigue involves the changes in peripheral mechanisms like altered membrane excitability, decrements of excitation-contraction coupling and fluctuations in muscular metabolic function (33). Arguably the most common method for analyzing muscular fatigue is with EMG readings, with observed change in the firing behavior of the motor units, and change in shape of the motor unit action potential (MUAP) being the two factors that affect the frequency spectrum in EMG signals that can indicate the onset of fatigue (54). Regarding more specific observation of the EMG signal, recording changes in the M-wave amplitude may indicate a peripheral issue with changes in the sarcolemma, related to slowed impulse conduction velocity (11). M-wave amplitude refers to the summation of electrical activity within motor units and their motor axons that were subjected to depolarization from a stimulus, and can assess peripheral neuromuscular properties without involving the CNS (30).

Another factor to consider with the change in muscular activity after muscular fatigue is the change in motor unit behavior. Under normal conditions, muscle contraction occurs by recruiting motor units in order, according to Henneman's size principle, of increasing size based on threshold level from low to high (23). Recruitment order during electrical stimulation seems to follow a reversed motor unit recruitment order compared to voluntary contraction, defying Henneman's size principle (22). Similarly, with the onset of fatigue the process of recruitment order is also disturbed with more variability present, as well as a modulated discharge rate during submaximal contraction (10). Considering examples of recruitment order and fiber type, the difference between the rate of decline in motor unit conduction velocity of the vasti muscles between endurance athletes and strength trained athletes has been shown to be determined mainly based on muscular composition, with endurance trained individuals exhibiting a greater time to task failure, and lower motor unit discharge rates during submaximal contractions (55).

Although the role of group III and IV muscle afferents is not well understood, their activation may inhibit central motor drive, and reduce the tolerance of peripheral fatigue in endurance sport (27). These afferents may also have varying effects between the extensors and flexor muscles, depressing extensor motoneurons and facilitating flexor motoneurons (56). These types of perturbations in motor unit activity act as a regulating mechanism to protect the muscle as it approaches peripheral fatigue, but is consequently a limiting factor to performance. Activation of group III and IV muscle afferents have been linked to considerably reduced central motor output via the spinal and supraspinal levels (23,36). The Hoffman reflex (H-reflex) amplitude, which is elicited via electric stimulation and is an indicator of the quality of synaptic transition (57), also has been shown to decrease in sustained submaximal contractions that is said to be mediated by group III and IV afferents, but not in intermittent submaximal contractions

(58). This difference in results between sustained submaximal contractions and intermittent submaximal contractions is explained by the duration of contraction, and when sustained, considerably more metabolite accumulation is present, leading to inhibition (58). All of this being considered, what to expect from particular fatigue protocols is an important step in the muscular fatigue research process. However, the influence of eccentric muscle action is yet to be considered, as the majority of research has investigated mostly sustained muscle contraction, and concentric muscular fatigue.

The analysis of motor drive is possible by using integrated EMG (iEMG), by observing the quantity of max contraction, and can indicate the level of muscle excitation achieved (11). The excitation rate can be derived from iEMG when expressed as a percentage of max contraction. IEMG, in addition to max contraction, can be utilized with observing constant repetition of submaximal contractions, as is present with running. Observing this activity with running can be useful because the progressive increase in iEMG indicates greater motor unit recruitment and increased firing rates. With respect to fatigue, excitation frequency tends to decrease, and is associated with decrements in force output (11,44). A decrease in excitation frequency results in a range of lower frequency muscle fibers to be recruited, which have a lower capacity of force generation (11). Since excitation rate decreases, lower frequency muscle fibers are recruited with fatigue, and there are differences in contractile requirements for different muscles, observing muscle contraction at a motor unit level may be useful.

Muscle Action Type and Rate of Fatigue with Running

Muscle contraction type (concentric, isometric, eccentric) is a basic concept relating to human movement control, and its relationship to the mechanics of motion spans a wide variety of topics from myopathy, its role during exercise, and its importance in other fields that have been researched for over a century. Although running is a constant cycle of repetitive multi-joint movements to transport the body above the ground, breaking the cycle into phases makes it possible to observe how the body transitions from one point to the next. While in motion, the contraction type of each muscle changes throughout the running cycle, and the forces required to mobilize the joints during each phase varies for forward motion to be initiated and sustained. Due to the inherent nature of the change in forces both acting on the body via ground contact, and internally using torque to move the limbs, it follows that some muscles contribute considerably more force to create motion, and some muscles also play greater roles in stabilizing the limbs to maintain joint integrity. Moreover, the repeated lengthening and shortening of the muscles, respectively, have properties unique to their action that make them more or less susceptible to fatigue, and will contribute differently to changes in performance. Therefore, to better understand the affect muscular fatigue can have on performance, understanding how shortening and lengthening actions differ regarding their level of contribution while running will afford greater insight into the muscular compensations that occur.

Phases of Running and Muscular Involvement

The specific focus of this research literature review is on lower body running mechanics, and the running cycle will be broken down briefly accordingly. Firstly, the most basic phases of the running cycle are broken down according to the motion of one leg at a time. Initial contact (IC) and toe off (TO) are part of the stance phase, and the swing phase occurs just before terminating the cycle upon IC once again on the opposite leg. IC during the stance phase is termed absorption due to the fact body weight is coming in contact with the ground, and ground reaction forces are being absorbed into the limb. As the momentum of the body during stance is being transferred forward and downward, the weight of the body goes from absorption to generation to propel the body forward and upward, where TO terminates this phase of force generation before the next leg initiates contact (IC) and the cycle repeats (59).

Next, the muscular activity that occurs throughout the running phase in specifically the quadriceps and hamstring muscles will be described. The quadriceps muscles begin contraction prior to IC, and the rectus is the only muscle active during midswing. The hamstrings are active during the second half of swing and first half of stance, play a key role in counteracting forward momentum of the tibia prior to IC, facilitate energy transfer between legs, and generally act eccentrically during stance and concentrically during swing (59). The difference between moments about the knee for running and sprinting are similar, but the magnitude of the peak knee extensor moment is usually more when running, with greater ROM about the knee during absorption (59). In the second half of swing, hamstring activation increases for initial contact to counterbalance the rapid knee extension that follows. The quadriceps contracts eccentrically to accommodate increasing knee flexion, and generates power about the knee by concentrically contracting in the second half of stance to continue propelling the body upward and forward (59).

Internal Mechanisms of Muscle and Contribution to Fatigue

One of the earlier contributors to the viscoelastic properties of muscle regarding the force-velocity relationship of muscular contraction to movement velocity over time is from Hill. Hill's profound discovery of the force-velocity nature very generally posits that there is a mechanical efficiency in the spectrum of contraction types that are dependent on velocity and duration. According to Hill's model, there is an optimal movement velocity that correlates with the efficiency of force production potential over the duration of a muscular contraction (60). However, the shape of the force-velocity relationship has since been shown to exhibit a double-hyperbolic shape that deviates from Hill's initial conclusions (61–63). There is a certain breakpoint where a greater cross-bridge attachment is attenuated by a decrease in force per cross-bridge formed, which has been confirmed in moderately fatigued muscle fibers (61). This increase in cross-bridge attachment was reported by Jones and colleagues (2010), where the phenomenon was connected to fatigued muscles being more resistant to stretch, where the greater proportion attached could afford more rapid recruitment for force generation. The potential for deviation from the traditional force-velocity model from Hill creates further implication for injury risk with the introduction of fatigue into the muscles.

The length-tension relationship is inherent to muscular function, and is complexly variable (64). Peak eccentric knee flexor torque has been reported to decrease significantly after roughly 15-minutes of exercise (65), with reports of up to a 15% decrease in peak eccentric knee flexor torque after fatigue caused by repeat sprints (16). These observed decreases during running activity could be especially magnified during different phases of the running cycle. For example, in the hamstrings, peak musculotendon force, and negative work has been observed during the swing phase with increases in speed (18). Aside from increased muscular load, the decrease in torque production about the joints can be further compensated by the previously mentioned kinematic changes like increased knee-flexion upon ground contact, which is representative of changes in length-tension relationships for increased efficiency after the onset of muscular fatigue (35,66).

The role of muscular recruitment has been mentioned in a multitude of examples, and involves the quantity of motor units activated. But another concept, rate coding, involves the discharge rate of action potentials in motor units (67), which may be more relevant to running. Rate coding may more specifically define how muscle force control requirements are managed than with muscular recruitment. At intermediate and high forces, rate coding has been shown to have a greater responsibility for muscle force control changes, while lower forces are controlled by recruitment (68). Reports of rate of force development increases in rapid contractions have been linked to motor neuron’s ability to match force increases with increases in discharge rate of action potentials (67). But rate of force development is modulated by the motor unit’s threshold, and increases to maximal discharge rates are limited to high-threshold motor units (67). If considering the difference in discharge rate between muscle action types, shortening contractions require greater discharge rates compared to lengthening, however lengthening contractions have a greater capacity for force production (36,67). The differences between motor unit discharge rates, changes between different muscle contractions throughout the running cycle, and the additional presence of muscular fatigue may influence muscle action while in motion. The influence fatigue may have could create compensations that hinder performance and movement outcomes.

Various studies have established that there are neuromuscular differences exhibited from eccentric (lengthening) contractions compared to isometric (static) and concentric (shortening) contractions (25,40). Two outstanding factors concerning lengthening contractions is that, firstly, there is greater intrinsic force capacity available, and secondly, that the muscular force for lengthening must be less than the load being exerted, which is the opposite case for shortening contractions (38). When examining the differences in shortening and lengthening of muscle fibers during motion, the force-velocity relationship should be considered carefully because the contribution of peripheral and central mechanisms vary along this spectrum (38). However, this relationship has been controlled in an abundance of research by using isokinetic dynamometers to adjust the forces and joint angular velocities (2–4,21,55,65,69). So, shortening and lengthening actions can be controlled for research purposes to elicit more specific muscular fatigue environments, but it still stands that lengthening and shortening actions vary with regard to fatigue. Concentric contractions to fatigue show greater force decrements compared to eccentric contractions (16,70), but the contribution of peripheral mechanisms that cause this are different, mainly based on the greater energy requirements for concentric contraction (70). One of the main points of contention with lengthening contractions, is the neuromuscular control aspect that lengthening contractions contribute, and how that can change with the onset of fatigue. Specifically, with how those neuromuscular changes can be examined to avoid injury, and if there are specific neuromuscular changes in eccentric action that may have greater impact on injury risk. Thus, the difference in muscle action throughout the gait cycle, in addition to the presence of fatigue, may have interesting implications for injury risk during activity while running.

Few studies have incorporated local fatigue of muscles in the lower extremities, while also investigating fatigue’s effect on running mechanics (2–4), and fewer studies have investigated this specifically with fatigue of the hamstrings and quadriceps (2,3). Fatigue about the knee joint has been shown to result in increased knee flexion at initial contact on multiple occasions (2,3,5). Furthermore, coactivation between the quadriceps and hamstring muscles has been shown to increase, influencing the stability about the knee joint (2). The key component with previous research of fatigue about the knee joint is increased quadriceps muscle activation upon ground contact (2). The results from the aforementioned studies only investigated fatigue about the knee, and not with how running mechanics change if either the flexor or extensor muscle groups were fatigued independently. It is possible that this approach of independently fatiguing the flexors or extensors could have a considerable influence on the coactivation between the quadriceps and hamstrings, as well as the dynamics of muscle activation during stance, and potentially the rest of the gait cycle. However, due to lack of related local muscle fatigue research available for insight into this idea, further investigation is necessary.

Chapter 3: Methodology

Participants

Five recreationally active male (n=2) and female (n=3) college students were recruited for this study (23.60 +/- 1.14 years; 1.71 +/- 0.13 m; 67.60 +/- 14.50 kg). An *a priori* power analysis was used to determine a sample size of 15 was necessary for this study (alpha level = 0.05 and power of 0.8) (71–73). Subjects were required to meet ACSM guidelines for daily recommended activity of at least 30 minutes of moderate exercise three times per week (74), or run a minimum of 15 miles per week. Participants were excluded if they had history of a lower extremity injury or pain that caused inability to run for more than one month for at least six months before testing, or any neurological disorder that may have affected their performance in this study. All subjects were required to complete a university approved informed consent document and health history forms before participation.

Experimental Design

This study was a controlled laboratory study. All subjects participated in two separate fatigue protocol sessions.

Instruments & Equipment

A Cybex dynamometer (HUMAC 2009v.9.6.0: NORM, Medway, MA) was used to assess knee flexor and extensor maximum voluntary isometric and isokinetic contractions, as well as for the isokinetic knee flexor or extensor fatigue protocol. Kinematic data were collected with a passive, 15-camera, 3-D Vicon Nexus FX motion capture system (Vicon Inc., Denver, CO, USA) and Nexus 2.9.3 software (Oxford Metrics, Ltd, Oxford, UK), sampling at 179.104 Hz. A 5-minute warm-up at self-selected pace preceded the pre-fatigue run, and subsequent 2-minute immediate post-fatigue, and 12-minute post-fatigue runs took place on a AMTI Dual Belt

Front/Rear Force Instrumented Treadmill (Advanced Mechanical Technologies Inc., Watertown, MA, USA) sampling data at 1074.63 Hz to assess ground reaction force data.

Procedures

All participants in this study visited the Ball State University Biomechanics Laboratory on two occasions for two sessions lasing approximately 90 to 120 minutes, with seven to ten days (mean = 8.2 days) between each session. Participants were randomly assigned to either hamstring or quadriceps muscular fatigue sessions for the first session and completed the other muscular fatigue the following session. Prior to participation in the study a university approved consent form and general health history questionnaire were completed by all participants. During each session, participants performed pre-fatigue treadmill running, isometric and isokinetic strength measurements, isokinetic fatigue protocol, post-fatigue treadmill run, and a 12-minute post-fatigue run where treadmill-running kinematics, kinetics, and electromyographic (EMG) activity were recorded during all running sessions, both pre- and post-fatigue.

Participants changed into compression clothing and laboratory supplied cross-trainer athletic footwear (Women's Nike T-Lite VIII Leather: Men's Asics Gel 180TR). Next, anthropometric measurements were taken for height, weight, inter-ASIS distance, leg length, knee width, and ankle width. Prior to data collection, retroreflective markers were placed on the body using a modified Plug-in Gait Model (Vicon Motion System Ltd., Oxford, UK), and included the jugular notch of the sternum, xiphoid process, acromioclavicular joint, calcaneal tuberosity, 2nd metatarsal head, lateral side of the 5th metatarsal head, lateral epicondyle of femur, medial epicondyle of femur, lateral malleolus, medial malleolus, posterior superior iliac spine, shank, anterior superior iliac spine, and iliac crest, and inferior aspect of the right scapula.

Kinematic data were collected with a passive, 12-camera, 3-D Vicon Nexus FX motion capture system (Vicon Inc., Denver, CO, USA) and Nexus 2.9 software (Oxford Metrics, Ltd, Oxford, UK), sampling at 179.104 Hz. Standing static and dynamic calibration trials took place prior to warm-up to establish joint centers. A 5-minute warm-up on a SOLE treadmill (SOLE Fitness, Salt Lake City, UT, USA) at a self-selected pace preceded the pre-fatigue run. Participants were asked to warm-up at a self-selected pace, and in the last minute of their run to adjust the treadmill speed to the 3.61 m/s testing speed. After the warm-up, the participant then ran at 3.61m/s for two minutes on an AMTI Dual Belt Front/Rear Force Instrumented Treadmill (Advanced Mechanical Technologies Inc., Watertown, MA, USA) sampling at 1074.63 Hz while ground reaction force (GRF), electromyography (EMG), and kinematic data were recorded.

Subjects then completed bilateral isometric and isokinetic strength measurements on a Cybex Norm isokinetic dynamometer (Lumex Corporation, Ronkonkoma, NY, USA), and hook-and-loop straps used to stabilize the trunk, waist, and thighs. Strength measurements were used to monitor fatigue levels during the data collection period by using maximal torque values. Three maximal voluntary isometric contractions were performed at 30° of flexion for the hamstring tests, and at 60° of flexion for the quadriceps tests. A 1–2-minute rest was given prior to isometric tests, and the subject’s knee ROM was adjusted so 5-10° of extension was subtracted to allow the participant to maintain torque at or above the threshold required to continue the isokinetic movement resulting in 70-80° of knee extension ROM. Then, subjects completed a set of three practice isokinetic maneuvers at 60°/s to become acquainted with the isokinetic motion. After resting for one to two minutes, subjects were given verbal encouragement while completing three maximal isokinetic efforts at 60°/s. After peak concentric toque was determined, a threshold of 50% was used for the fatigue protocol. The strength tests were completed for the quadriceps or hamstrings based on the subject's random group assignment for the first session, and the second session covered the other muscle.

Each participant completed the fatigue protocol for the extensors and flexors on two separate days seven to ten days apart (mean = 8.2 days). The fatigue protocol consisted of continuous, bilateral concentric and eccentric knee-extension or knee-flexion efforts at 60°/s. When a participant could not attain their calculated threshold value for three consecutive repetitions, they were determined to be fatigued for one set. The participant was given one minute to recover after each fatigued set before repeating the fatigue protocol two more times for a total of three sets to the criterion level of fatigue. Upon completion of the three fatigued sets, the participant immediately completed the post-fatigue run for two-minutes at 3.61m/s. The final two-minute run took place 12-minutes after the fatigue protocol to assess changes that may have been present after a short recovery period. Data were collected for the first, middle, and last seven seconds of all runs.

Data Processing

Mean data from 5-7-consecutive steps of the participants' dominant leg were used for all kinematic parameters. Ground reaction forces from impact at initial contact were observed. Kinematic and kinetic data were low pass filtered using a dual-pass, zero phase shift Butterworth low-pass 15Hz filter. Initial contact angles, peak angles, and joint ROM changes were observed in the frontal and sagittal planes at the hip and knee. Joint ROM was calculated as the difference between the maximum and minimum joint angles during the stance phase for each joint, respectively. Force data were used to measure peak vertical impact GRF for both legs while running and to calculate joint moments and powers.

Statistical Analysis

A repeated-measures analysis of variance (RM-ANOVA) was used for each of the dependent variables to determine the influence of fatigue on the kinematic and kinetic variables tested. The two within-subject variables include pre- and post-fatigue, and the location of the fatigue protocol (knee flexors or extensors). When a significant effect for time (pre-fatigue, immediate post-fatigue, 2-minutes post-fatigue, 12-minutes post-fatigue), or muscle (quadriceps, hamstring) was observed ($p < 0.05$), pairwise contrasts were observed. All analyses were conducted using SPSS (version 26; IBM Inc. New York, NY) at $\alpha < 0.05$.

Chapter 4: Manuscript

THE EFFECTS OF LOCALIZED MUSCULAR FATIGUE ON LOWER BODY RUNNING MECHANICS

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Abstract

Background: Running is a popular form of exercise and inherent to many sports. Running while fatigued has been associated with decrements in performance and increased risk of acute and overuse running injuries. However, the relative contributions to running mechanics from individual muscle(s) have not been clearly established and could help further elucidate risk factors and anatomical structure foci during training. This study’s purpose was to analyze alterations in kinematic, kinetic, and ground reaction force (GRF) variables with the onset of localized fatigue. It was hypothesized that knee flexor and extensor fatigue on separate occasions would increase impact forces, joint angles, joint moments, and powers compared to pre-fatigue values.

Methods: Five healthy college-aged adults (2 males, 3 females: 23.60 +/- 1.14 years; 1.71 +/- 0.13m; 67.60 +/- 14.50kg) ran at 3.61m/s prior to and following isokinetic knee flexion and extension (concentric and eccentric) efforts for a total of three, two-minute runs. Motion capture and force data were used to calculate joint motion and loading throughout each run. Data were analyzed using RM-ANOVA evaluating kinematic and kinetic changes following fatigue of knee flexors and extensors for each run.

Results: Maximum braking force significantly increased from immediate post-fatigue to two-minutes post-fatigue ($p=0.003$; $\eta^2_p=0.677$). Peak vertical GRF significantly ($p<0.05$) decreased from pre-fatigue (2.79 +/-0.09BW) to immediate post-fatigue (2.46+/-0.10BW) of the quadriceps. Propulsive knee power significantly ($p<0.05$) decreased from pre-fatigue (11.32+/-1.74Nm/kg) to immediately post-fatigue (6.93+/-0.90Nm/kg) of the quadriceps. Knee abduction moments were significantly higher ($p=0.001$; $\eta^2_p=0.960$) for running measures following hamstring fatigue over that of quadriceps fatigue.

Discussion: Quadriceps fatigue showed the greatest pre-fatigue to immediately post-fatigue changes. Vertical impact peak force and propulsive knee power decreased significantly more immediately post- quadriceps fatigue than hamstring fatigue. Horizontal braking forces exhibited similar changes for both muscles over time, having significantly increased during the fatigued run.

Introduction

Running for exercise is a popular choice for many people. In the US, from 2009-2015, 8.6% of people aged 15 and older (approximately 17 million people) reported running for physical activity (Bureau of Labor Statistics, 2015). However, running is notorious for its relationship to lower body injuries. Running related injuries per 1000 hours of running have been reported to range from as little as 2.5 injuries in long-distance track and field athletes, to as high as 33.0 injuries in novice runners (1). Novice runners are impacted by injuries at rates considerably higher than their recreational running peers (33 vs. 7.7 injuries per 1000 hours of running) (1). All levels of running have some degree of inherent risk of injury to the runner. However, the lowest proportion of injuries seem to occur in moderate duration and intensity categories of running like jogging, while sprinting and ultra-marathon running have been shown to result in the greatest proportion of injuries of runners (7).

Running experience and duration have been extensively researched regarding injury rate, but muscular fatigue's influence on injury remains unclear. Fatigue is generally defined as a decrease in the capacity of voluntary muscle force production (11–13). Localized muscle fatigue is generally limited to fatigue of a single muscle, or muscle group, acting about a particular joint of interest. Localized fatigue also involves decreased capacity of voluntary muscle force production, changes to movement patterns, and decrements to motor control and task performance (2–4,14). Localized muscular fatigue has the benefit of observing changes at specific joints or muscle(s) that occur between pre- to post-fatigue performance. Isolating fatigue to an individual joint or muscle can provide insight into how task performance is influenced by fatigue, and further understanding into potential injury risk factors caused by altered mechanics at the fatigued joint and the surrounding non-fatigued joints.

One benefit of utilizing localized muscle fatigue is that while changes may occur at the isolated joint, the capabilities of the surrounding joints are not impaired and may provide insight into the compensations that may occur during fatigue or injury. Following isokinetic knee joint fatigue, researchers reported increased knee flexion at impact along with increased knee joint excursion, resulting in decreased knee joint stiffness (2,3). The researchers further suggested that increased quadriceps muscle activation was a key indicator of fatigue, and the body's response to compensate for the loss in strength. By increasing knee flexion at impact the quadriceps may be placed in a more effective joint angle to facilitate force production while fatigued (2). Further, through the increase in knee flexion there may be an attenuation of the impact ground reaction force (GRF), in addition to a slightly longer period of ground contact to maintain the necessary force impulse, while reducing the magnitude of the peak impact force absorbed by the body (24). Fatiguing the hamstring and quadriceps muscles independently could result in altered force output in these muscles and may create instability about the knee. Examining compensations that occur at joints both proximal and distal to the fatigued muscle and joint may provide further insight into the overall role, and potential impairments occurring because of isolated muscular fatigue.

Impaired running economy is generally determined by decreased joint moments and powers, implying increased stress about a joint, and detriments to propulsive or absorptive power. Marathon running as a prime example of the onset of fatigue, primarily influencing knee extension torque (15). The repeated eccentric muscle action demanded by running activity has been shown to debilitate muscular force production capacity (25). It is possible that as a runner becomes more fatigued, resisting weight acceptance will manifest via increase absorptive power at the knee, and decreased propulsive power at the knee to allow the body to continue moving optimally through space. These prospective increases in joint loading post-fatigue may cause these changes as reports of the greatest magnitudes of net torques, powers and work were at the hip and knee in the sagittal-plane (26). Decrements in optimal joint motion under the loads placed on the body, especially with the onset of fatigue, may result in considerable deviations in joint torques and power that ultimately hinder running performance.

Materials & Methods

Experimental Procedures

Five recreationally active male (n=2) and female (n=3) college students were recruited for this study (23.60 +/- 1.14 years; 1.71 +/- 0.13 m; 67.60 +/- 14.50 kg). An *a priori* power analysis was used to determine a sample size of n=15 was necessary for this study (alpha level = 0.05 and power of 0.8) (71–73). Subjects were required to meet ACSM guidelines for daily recommended activity of at least 30 minutes of moderate exercise three times per week (74), or run a minimum of 15 miles per week. Participants were excluded if they had history of a lower extremity injury or pain that caused inability to run for more than one month during the previous six months before testing, or any neurological disorder that may have affected their performance in this study. All subjects were required to complete a university approved informed consent document and health history forms before participation.

All participants in this study visited the Ball State University Biomechanics Laboratory on two occasions for two sessions lasing approximately 90 to 120 minutes, with seven to ten days (mean = 8.2 days) between each session. Participants were randomly assigned to either hamstring or quadriceps muscular fatigue sessions for the first session and completed the other muscular fatigue session the following week. Upon entering the lab, participants completed a university approved consent form and general health history questionnaire. During each session, participants performed pre-fatigue treadmill running, isometric and isokinetic strength measurements, isokinetic fatigue protocol, post-fatigue treadmill run, and a 12-minute post-fatigue run where treadmill-running kinematics, kinetics, and electromyographic (EMG) activity were recorded for all running trials both pre- and post-fatigue.

Participants changed into compression clothing and laboratory supplied cross-trainer athletic footwear (Women’s Nike T-Lite VIII Leather: Men’s Asics Gel 180TR). Next, anthropometric measurements were taken for height, weight, inter-ASIS distance, leg length, knee width, and ankle width. Prior to data collection, retroreflective markers were placed on the body using a modified Plug-in Gait Model (Vicon Motion System Ltd., Oxford, UK), and included the jugular notch of the sternum, xiphoid process, acromioclavicular joint, calcaneal tuberosity, 2nd metatarsal head, lateral side of the 5th metatarsal head, lateral epicondyle of femur, medial epicondyle of femur, lateral malleolus, medial malleolus, posterior superior iliac spine, shank, anterior superior iliac spine, and iliac crest, and inferior aspect of the right scapula.

Kinematic data were collected with a passive, 12-camera, 3-D Vicon FX motion capture system (Vicon Inc., Denver, CO, USA) and Nexus 2.9 software (Oxford Metrics, Ltd, Oxford, UK), sampling at 179.104 Hz. Standing static and dynamic calibration trials took place prior to warm-up to establish joint centers. A 5-minute warm-up on a SOLE treadmill (SOLE Fitness, Salt Lake City, UT, USA) at a self-selected pace preceded the pre-fatigue run. Participants were asked to warm-up at a self-selected pace, and in the last minute of their run adjust the treadmill speed to 8 mph, which was equivalent to the 3.61 m/s (8.08 mph) testing speed. After the warm-up, the participant then ran at 3.61m/s for two minutes on an AMTI Dual Belt Front/Rear Force Instrumented Treadmill (Advanced Mechanical Technologies Inc., Watertown, MA, USA) sampling data at 1074.63 Hz while ground reaction force (GRF), electromyography (EMG), and kinematic data were recorded.

Following the pre-fatigue run and prior to the fatigue protocol, subjects completed bilateral isometric and isokinetic strength measurements on a Cybex Norm isokinetic dynamometer (Lumex Corporation, Ronkonkoma, NY, USA), and hook-and-loop straps used to stabilize the trunk, waist, and thighs. Strength measurements were used to monitor fatigue levels during the data collection period by using maximal isokinetic concentric torque values. Three maximal voluntary isometric contractions were performed at 30° of knee flexion for the hamstring tests, and at 60° of knee flexion for the quadriceps tests. A 1–2-minute rest was given prior to isometric tests, and the subject’s knee ROM was adjusted so 5-10° of extension was subtracted, allowing the subject less ROM during extension in order for the torque threshold required to continue the isokinetic movement to be sustained. Knee ROM after adjusting extension ROM was still ensured to be at least 90°, however most participants could only maintain the isokinetic maneuver between 70-80° of knee extension ROM. Then, subjects completed a set of three practice isokinetic maneuvers at 60°/s to become acquainted with the isokinetic motion. After resting for one to two minutes, subjects were given verbal encouragement while completing three maximal isokinetic efforts at 60°/s. After a peak torque was determined, a threshold of 50% was used for the fatigue protocol. The strength tests were completed for both quadriceps and hamstrings based on the subject's random group assignment.

Each participant completed the fatigue protocol for the extensors and flexors on separate occasions. The fatigue protocol consisted of continuous, bilateral concentric and eccentric knee-extension or knee-flexion efforts at 60°/s. When a participant could not attain their calculated threshold value for three consecutive repetitions, they were determined to be fatigued for one set. The participant was given one minute to recover after each fatigued set before repeating the fatigue protocol two more times for a total of three sets. Upon completion of the three fatigued sets, the participant immediately completed the post-fatigue run for two minutes at 3.61m/s. The final two-minute run took place 12-minutes after the fatigue protocol to assess changes that may have been present after a short recovery period. Data were collected for the first, middle, and last 20 seconds of all runs (20 sec, 50-70 sec, 100-120 sec, respectively).

Data Processing

All motion capture data as well as ground reaction force were collected using Vicon Nexus software (2.11) with post-processing and inverse dynamics performed using Visual 3D (C-Motion, Germantown, MD, USA). Mean data from 5-7-consecutive steps of the participants' dominant leg were used for all kinematic parameters. Ground reaction forces from impact at initial contact were observed. Kinematic and kinetic data were low pass filtered using a dual-pass, zero phase shift Butterworth low-pass 15Hz filter. Initial contact angles, peak angles, and joint ROM changes were observed in the frontal and sagittal planes at the hip, knee, and ankle. Joint ROM was calculated as the difference between the maximum and minimum joint angles during the stance phase for each joint, respectively. Force data were used to measure peak vertical impact GRF for both legs while running and to calculate joint moments and powers.

Statistical Analysis

A repeated-measures analysis of variance (RM-ANOVA) was used for each of the dependent variables to determine the influence of fatigue on the kinematic and kinetic variables tested. The two within-subject variables include pre- and post-fatigue, and the location of the fatigue protocol (knee flexors or extensors). When a significant effect for time (pre-fatigue, immediate post-fatigue, 2-minutes post-fatigue, 12-minutes post-fatigue), or muscle (quadriceps, hamstring) was observed ($p < 0.05$), post hoc pairwise contrasts were performed. Results were also evaluated based on partial eta squared effect sizes according to the established values known to be η^2_p=0.01 (small), 0.06 (medium), 0.14 (large) (75). All analyses were conducted using SPSS (version 26; IBM Inc. New York, NY).

Results

All participants completed the three, 2-minute running periods (pre-fatigue, immediate post-fatigue to 2-min post-fatigue, 12-min post fatigue), and all other aspects of the study without difficulty.

Kinematics

Data collected on kinematic variables did not reach the level of significance on any of the main effects or the interactions of muscle and time. While the sample size was relatively small additional considerations were given to the associated effect sizes for each measure to determine if a larger sample could elevate the differences to the level of statistical significance. (Table 1). Hip extension angle for the main effect of time (p=0.065, η^2_p=0.441) revealed a decrease in hip extension after quadriceps fatigue from pre-fatigue (-19.146 +/- 1.336°) to immediate post-fatigue (-14.509 +/- 0.806°). Sagittal plane knee flexion at initial contact approached significance for the main effect of time (*p*=0.088, η^2_p=0.409), showing that knee flexion angles at initial contact decreased from pre-fatigue after completing both fatigue protocols, but were higher overall in the latter half of the trials for the hamstring fatigue session. The main effect between quadriceps and hamstring muscles accounted for ~20% (η^2_p=0.205) of the variability in sagittal plane knee flexion at initial contact. The main effect over the three 2-minute running periods accounted for ~25% (η^2_p=0.246) of the variability in sagittal plane minimum hip velocity.

Knee abduction angle at initial contact approached significance for the interaction effect of muscle*time (*p*=0.051, η^2_p=0.465), indicating increased knee abduction angle at the point of initial contact, and a greater knee abduction for the quadriceps session than hamstring session over time. Peak transverse knee internal rotation angle approached significance for the main effect of time (*p*=0.066, η^2_p=0.273), showing an observable increase in knee internal rotation after hamstring fatigue from immediate post-fatigue (2.492 +/- 4.843°) to 2-minutes post-fatigue (5.404 +/- 3.708°). Finally, transverse plane peak knee velocity approached significance for the main effect of time (*p*=0.093, η^2_p=0.402), with a roughly 14% greater velocity at the 12-minute post-fatigue run for the hamstring fatigue session than quadriceps fatigue. The main effect over the three 2-minute running periods accounted for 25% (η^2_p=0.250) of the variability in peak transverse plane knee velocity.

Ground Reaction Forces

When contrasting across time, there was a significant main effect for maximum horizontal braking force [$F_{(1,4)}$=8.401; *p*=.003; η^2_p=0.677], with a decrease in force from pre-fatigue to immediately post-fatigue, increase in force throughout the post-fatigue run, and another decrease in force following the 12-minute recovery period that did not recover to pre-fatigue values for either muscle groups. As previously mentioned with kinematics, additional variables approaching significance with considerable effect sizes were explored to identify trends and potential measures of interest for future investigations.

The main effect between quadriceps and hamstring muscles accounted for ~23% (η^2_p=0.228) of the variability for minimum braking force. Peak vertical ground reaction force (GRF) approached significance for the main effect of time (p=0.089, η^2_p=0.407) indicating a decrease in GRF post-fatigue, with quadriceps fatigue exhibiting the greatest overall difference in force from pre-fatigue (2.789 +/- 0.093 N/BW) to immediate post-fatigue (2.459 +/- 0.096 N/BW). Despite the main effect for peak GRF this measure also had a significant muscle*time interaction effect [$F_{(1,4)}$=6.083; p=0.009; η^2_p =0.603]. Figure 5 illustrates the nature of the interaction in which there were considerably different pre-fatigue values between the quadriceps and hamstring fatigue test days, which resulted in a considerably greater decrease in GRF from pre- to immediately post-fatigue following quadriceps fatigue.

Kinetics

The within-subjects effect of muscle for maximum sagittal (knee flexion) and frontal plane knee moments (knee abduction) were significant [$F_{(1,4)}$=10.424; p=.032, η^2_p = .723), [$F_{(1,4)}$=96.005; p=0.001; η^2_p =0.960), respectively (Table 2). Maximum sagittal plane knee moments were, on average, 13.72% higher for the quadriceps session for all time points than the hamstring fatigue condition. During all three running periods the hamstring-fatigue session resulted in 85.74% higher knee abduction moments than the quadriceps-fatigue session.

There was a significant main effect of time (p=0.008, η^2_p =0.61) for maximum knee abduction moments, but significantly declined after quadriceps fatigue from pre-fatigue to immediate post-fatigue. The main effect over the three 2-minute running periods accounted for ~25% (η^2_p =0.253) of the variability for knee abduction moment.

A significant [$F_{(1,4)}$=3.49; *p*=0.050; η^2_p=0.466] muscle*time interaction effect for maximum (propulsive) knee power was found with a significant decline in power from pre- to post-fatigue, and an increase in power from immediate post-fatigue to 2-minutes post-fatigue . In contrast, minimum (absorptive) knee power was not significant for either main effects of muscle or time. A significant [$F_{(1,4)}$=4.594; *p*=0.023; η^2_p=0.535] main effect of time for maximum knee power was found with a roughly 48% decrease in knee power from pre-fatigue to immediately post-fatigue, and followed by a 35.5% increase in knee power from immediate post-fatigue to 2-minute post-fatigue run.

In addition to the significant kinetic effects revealed in this study a number of additional kinetic measures approached significance or had moderate to large effect sizes. Maximum hip power approached significance for time (*p*=0.069, η^2_p =0.311), where hip power after quadriceps fatigue slightly declined from pre-fatigue to immediate post-fatigue, and slightly increased from pre-fatigue to immediate post-fatigue for the hamstring fatigue session, however both conditions had the lowest hip power magnitude at 12-minute post-fatigue. The main effect over the three 2-minute running periods accounted for ~20% (η^2_p =0.205) of the variability for hip power max.

Discussion

The purpose of this study was to assess the influence of quadriceps or hamstrings fatigue, in isolation, on running mechanics and ground impact forces and to quantify the short-term recovery process following acute concentric and eccentric fatigue. Due to the multifactorial nature of running-related overuse injuries (23,44,49,76–78), the present study sought to separate previous single joint fatigue protocols into two separate fatigue sessions focusing on the quadriceps and hamstring muscles independently. Previous research (34,71,72,78) found significant differences in lower body running mechanics, and muscular activation changes following localized isokinetic muscular fatigue protocols of the knee and ankle joints that specified local changes that may lead to running-related overuse injuries. Considering that the quadriceps and hamstring muscles are differentially activated during the stance phase, the current study independently fatigued the knee flexors and extensors to provide additional insights into the role played these muscles during running. Additionally, identifying the compensatory strategies for fatigue exhibited by the knee flexors and extensors may provide additional insights into clinical pre- and re-habilitation applications and help to contribute to performance enhancement in running.

Several significant findings and additional moderate to large effect sizes were revealed and provide evidence that individual muscle groups differentially influence running mechanics. Overall, individually fatiguing the knee flexors and extensors was observed to influence coordination about the knee joint in different ways, indicating different muscular compensation strategies used by the runner following the onset of fatigue for the quadriceps and hamstrings. The greatest degree of change in running mechanics in the current study occurred at the knee, as hypothesized, but changes were also elicited in other areas including hip power generation, peak vertical ground reaction forces (GRF) and minimum braking forces during the stance phase. Additionally, the difference in frontal plane (abduction) moments following fatigue between the two muscle fatigue protocols has provided additional details that were unexplained by previous literature but could be influenced by the medial vs. lateral musculature of the muscle groups fatigued. Future studies involving additional fatigue protocols may help to further explain differences and strategies to help reduce the influence of fatigue and running related performance and injury mechanisms.

Quadriceps Muscle Fatigue Effects

Previous research investigating the effects of whole-body fatigue (5,9,15) reported altered hip and knee motion post-fatigue, including increased hip and knee range of motion (ROM), and decreased force production. Localized fatigue protocols (34,35,71,72,79) found similar alterations to joint motion, but observed more specific changes, like those that are unique to ankle joint fatigue (34) that were not present when the localized fatigue is moved proximally to the knee joint. The current study sought to assess how the individual knee extensors and flexors would influence gait when fatigued, and to follow the progress of fatigue during a short-term recovery period. During stance, the present results revealed a decrease in hip extension angle from pre- to immediate post-quadriceps fatigue. Maximum hip extension occurs just prior to toe-off (59), and less hip extension post-fatigue of the quadriceps could indicate hip flexor tightness, or fatigue of the hip flexor (rectus femoris), but this would require EMG activity for better understanding. In the current study the decrease in hip extension post-fatigue of the quadriceps did not significantly impact the maximum power generated at the hip between pre- and post-fatigue running. Yet, a large effect size ($\eta^2_p = .311$) indicated that change in hip power occurred across the three two-minute running periods and may have been the result of the hip flexors resisting maximal hip extension. This could imply that hip extension from pre-fatigue to immediate post-fatigue during stance was not significantly limited prior to toe-off, and therefore did not decrease power generation at the hip. However, at 12-minutes post-fatigue, hip power was reduced in magnitude by ~46% below pre-fatigue values following quadriceps fatigue. This finding suggests that the decline in power generation could be due to a decreased hip extension moment during this time contributing to less power generated, a slight decline in effort during the third run, or an additional factor with muscular activity that requires EMG to better analyze this result.

Running economy is an important metric in determining how running performance is impacted, which can be quantified by changes in torque production and propulsive or absorptive power (42,80). Reduced knee extension torque was previously described as a detriment of fatigue from marathon running (15). In the current study, maximum knee extension moments and powers were significantly affected by fatigue, as the knee extension moment decreased by ~22% during stance, and knee power generation decreased by ~48% immediately post-fatigue of the quadriceps. It is important to point out that the mean knee extensor moments at the knee were considerably higher for the quadriceps testing session than for the hamstring session during the pre-fatigue run. To that end, when contrasting to previous research the values obtained during the hamstring session (26,81) closely approximated past research values. One potential explanation for the different pre-fatigue levels could be attributed to four of the five participants completing the hamstring session first, despite the randomization of testing sessions. Consequently, as a result of performing the experiment previously the majority of quadriceps fatigue sessions were on the second session and participants may have become more acclimated to running on the instrumented treadmill. Furthermore, maximum knee extension power was lower at 12-minutes post-fatigue than pre-fatigue values by ~19% after quadriceps fatigue, and only ~1% following hamstring fatigue. The differences in knee extension power between quadriceps and hamstring fatigue indicate how the hamstring fatigue did not have an additional influence on knee extension. This finding could support why hip extension was limited by the quadriceps as the substantial decline in knee power could have been limited by hip extension ROM. Future research should observe changes that may occur distally at the ankle to gather a more complete picture of recovery in the lower body.

Lower extremity joint kinetics have been shown to change as a function of different factors like running speed (26,82), running phase (18,19), and fatigue (83,84). Some studies have reported deviations in knee adduction moments (85), and hip abduction moments (79) and have been associated with overuse injuries. In the present study, knee abductor moments for the hamstring condition were approximately 85% higher than quadriceps values for all three two-minute runs, but it is unclear why the pre-fatigue values for both fatigue protocols were dissimilar. Although knee abductor moment was significantly different between muscles, the changes exhibited over time were steady and no substantial increases or decreases were observed between the three running conditions. This difference in knee abductor moment between hamstring and quadriceps sessions is something unique to the present literature. Motion at the knee in the frontal plane is generally limited as the surrounding structure is largely comprised of ligaments and muscles that act mainly as stabilizers, and are the main structure for injury risk (42). The greater knee abduction moments observed in this study could be a function of the majority of participants being females, and females have been shown to display greater knee valgus than male counterparts during drop landing tasks, running, and cutting (86–89). The present study found that internal knee abduction moment following quadriceps fatigue was significantly lower across all time points than the hamstring fatigue protocol. The main effect of muscle explained roughly 72% (η^2_p=0.723) of the variance for knee abduction moment. Similarly, the knee abduction angle at impact was approximately 31% lower for quadriceps fatigue than hamstring fatigue, and the interaction of muscle*time explained ~47% (η^2_p=0.465) of the variance in knee abduction angle at impact. This difference in knee abduction moment following quadriceps fatigue indicates a lesser knee abduction moment for quadriceps fatigue (Figure 9). The combination of greater knee adduction angle at impact and decreased internal knee abduction moment could be interpreted as a decrease in coordination during stance. However, frontal plane motion are difficult to ascertain since frontal plane motion at the knee is typically minimal, being restricted mainly by the collateral ligaments (42). Literature covering this area is sparse with regard to muscular fatigue and its impact on running mechanics and is in need of further support to gather more robust conclusions. Again, as mentioned previously, the four subjects that completed the hamstring session first may have skewed results due to acclimation to the study protocol and the instrumented treadmill. Future research should consider an additional acclimation period. Potentially including a longer pre-fatigue run, or a designated run prior to preparing subjects with markers and sensors if using an instrumented treadmill, or equipment that may have a learning curve and requires time to become adjusted to for participants.

There are conflicting reports regarding changes observed in ground reaction force (GRF) measurements post-fatigue, with some studies indicating that whole-body fatigue caused no change in these measures (5), while studies utilizing localized ankle-joint fatigue reporting increased peak vertical GRF and loading rate (34). Although the GRF changes in the current study were not significant, following quadriceps fatigue the pre-fatigue to immediate post-fatigue impact peak force decreased by ~13%, which is in alignment with previous whole-body fatigue protocols (5). The result of a non-significant change in impact peak following knee musculature fatigue may help to further illustrate the debilitating effects of fatigue about the ankle joint. Considering that ankle-joint fatigue has been specified as the contributing factor to increased ground reaction forces (34) and a control mechanism for force attenuation at ground contact (42), and joint coordination (71,72) the non-significant change following quadricep of hamstring fatigue help to further confirm the limited role in altering ground reaction force played by muscles acting at the knee joint. Despite the nonsignificant findings in the current study the observed decrease in peak impact force post-fatigue may be still serve as a protective mechanism exhibited by proper running mechanics, as previous research reported that participants with lower vertical force impact peak were at lower risk of overuse running injuries (90).

Horizontal braking force has been reported to be a more important indicator of running-related overuse injury in comparison to vertical ground reaction forces due to human bone structure and its ability to resist compressive loads over that of horizontal shearing forces associated with larger horizontal braking forces (84). Following the onset of fatigue horizontal braking forces were decreased slightly for both quadriceps and hamstring fatigue but increased by the end of the two-minute post-fatigue run. There is little literature that describes fatigue’s influence on braking forces during running, but a study that simulated fatigue concluded it had a minimal effect on GRF measures (91). However, runners in the present study exhibited a more extended leg during stance, were more extended at the hip, and hip velocity declined all immediately post-fatigue. These changes would suggest runners may have shortened their stride immediately post-fatigue, subsequently decreasing braking forces, and these variables eventually returned to within ~3% of pre-fatigue levels at the 12-minute post-fatigue period. Previous research has demonstrated that when runners actively increased step rate and shortened their stride, injury rates have been reported to decrease as a function of an overall softening of each step and reduction in braking force (84).

Hamstring Muscle Fatigue Effects

Increased knee flexion is a typical compensatory response with the onset of fatigue, having been previously reported during whole-body fatigue from running (5) and localized fatigue of the knee (72). Similar to previous findings (5,72), in the present study, knee flexion angle increased by ~12% at initial contact immediately following the hamstring fatigue protocol. In addition to reduced knee flexion, the hip extension velocity decreased by ~62% immediately-post fatigue. Reduced knee flexion would indicate greater knee extension during stance, and consequently could be indicative of shorter step length. Although step length was not part of this study's analysis, participants would ultimately need to maintain the testing speed while on the treadmill in some way, either through a reduction in hip extension, which was shown, along with reduced hip extension velocity that would require increased step frequency and shorter stride length. Participants likely shifted to a more economical running form to accommodate a lack of strength in the hamstrings following hamstring fatigue. It may be worth further research to analyze the swing phase and other temporospatial gait parameters and observe changes prior to initial contact to confirm the previous assumption. In the current study, during the two-minute post-(hamstring) fatigue run, participants began exhibiting greater peak knee flexion and knee flexion at initial contact, with the greatest increase in knee flexion at initial contact and knee flexion. The differences observed between previous research and the present study suggests that compensatory strategies are different between the quadriceps and hamstrings and may alter motion at different joints and time points as a result which can alter running performance.

With the development of increasing fatigue, previous research suggests eccentric hamstring peak torque production can significantly decrease and may play a role in increased risk of hamstring strain injury (92). It is interesting to note that the knee extensor moments following hamstring fatigue only showed at most an ~8% increase from immediate post-fatigue to two-minute post-fatigue, compared to an ~22% decrease from pre- to immediately post-quadriceps fatigue, and ~17% increase during the two-minute post-fatigue run. Considering that the primary focus of this study was during the stance phase, the involvement of the hamstrings is focused more at controlling hip motion while the quadriceps are more involved at the knee (42), at least until the late stance phase (42,43). Previous studies (6,17–19,71,93) have reported the importance of analyzing hamstring activity during late stance and the swing phase regarding greater overall stress on the hamstring muscles, which would need to be investigated in a future study.

Typically, internal or external rotation about the knee is limited during running, but knee internal rotation has been reported to increase during fatigue (79). When knee rotation is coupled with increased internal rotation velocity, previous studies have associated the two variables with running-related injury (85,94). From immediate post-fatigue to two-minutes post-fatigue of the hamstrings, internal rotation of the knee at impact increased by ~58% and peak internal rotation increased by ~74%, indicating that throughout the post-fatigue run the knee was more internally rotated during stance than during rested states. Peak transverse plane knee velocity remained consistent for both quadriceps and hamstring fatigue conditions but following the 12-minute post-fatigue rest period hamstring internal rotation velocity increased to ~14% greater than following quadriceps fatigue. Previous research (6,93) investigated interactions between fatigue and muscular activation and coordination became disproportionate amongst muscles in the hamstring and had an influence on time to exhaustion. Perhaps participant performance post-fatigue of the hamstrings in the present study was affected by disproportionate hamstring activation levels resulting in the aforementioned kinematic alterations while running. To more clearly elucidate these changes muscular activation levels would need to be observed using EMG to help explain the observed changes.

Currently, literature covering three-dimensional running mechanics of localized fatigue of the lower extremity is limited. Previous studies evaluated factors related to running-related overuse injuries, and reported increased maximum knee-varus velocities (79,85). Maximum knee-varus velocities while running have been observed to be higher in participants that were reported to have later developed iliotibial-band syndrome (85). In the present study, maximum knee abduction velocity gradually increased throughout the testing session following hamstring fatigue and had its greatest increase (14.65%) immediately-post fatigue. However, knee abduction angle at impact continually decreased from pre-fatigue to 12-minutes post-fatigue of the hamstrings in the present study. It appears that quadriceps fatigue has a greater influence on knee abduction angle than the hamstrings. Measuring hip abduction angle in addition to knee abduction angle may provide more detail on how fatigue influences frontal plane motion of the lower extremity.

Limitations

Certain limitations present during this study may have influenced results. Firstly, difficulties regarding participant recruitment substantially influenced the overall power for this study. Persistent issues with electromyography (EMG) significantly delayed participant recruitment and ultimately were not able to be analyzed for this study due to continued issues with EMG data processing and time constraints. Future research should include EMG data of specified lower extremity muscles to assess the individual role played by muscles in coordinating joint motion under the influence of fatigue while running. Additionally, fatigue level was assessed by estimating 50% of subject’s maximal voluntary efforts, which were assumed to be full effort. Under the circumstances where full effort was not given, fatigue level would have been overestimated and may have influenced results. Further, several participants indicated in the health-history questionnaire they had previous surgeries in one or both knees. Although all participants that indicated previous surgeries met inclusion criteria, and did not express discomfort during the testing procedures, it is possible that due to the nature of the fatigue protocol being specific to the knee, those individuals might have given lower overall effort during strength testing compared to not previously injured participants.

Conclusion

The present study analyzed the influence isolated quadriceps or hamstring fatigue on kinematic and kinetic variables during running and assessed the short-term recovery process following acute fatigue. Findings from this study indicated that individually localized muscle fatigue of knee flexors and extensors affected kinetics to a significant degree at the particular joint involved in the fatigue protocol, as well as at the hip joint, and showed some promising effect sizes and values that approached significance for kinematics. Changes in running mechanics and impact forces were observed to be more substantiated either immediately post-fatigue, or during the post-fatigue run. Few of the factors were observed to show differences during the short-term recovery period when compared to pre-fatigue values.

Though there were non-significant kinematic differences, we suspect that a greater sample size would provide the statistical power that would indicate joint range of motion may be influenced by fatigue of these muscles. Including muscular activation measurements may have provided another perspective to the internal changes that occurred in this study to better explain the differences between muscles that were not apparent with kinematic and kinetic data. Future research should consider including the ankle joint with the type of fatigue protocol included in the present study, as we believe there could be more informative potential with how ground reaction forces change considering the ankle’s role in controlling coordination at the distal lower extremity.

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Chapter 5: Discussion/Conclusion

This study initially aimed to address the gap in literature that had not yet identified how fatigue influences the quadriceps and hamstring muscles independently, on muscular activation changes, and kinematic and kinetic measures while running. Muscular activity data was collected during data collections using EMG sensors on the dominant leg of participants. Ultimately the EMG data that was collected during this study's data collections was not used due to persistent issues with pairing the EMG sensors to our lab collection computer that did not allow us to collect muscular activity while the sensors were triggered. During the troubleshooting process, to continue using EMG, considering it was a crucial aspect to the proposed thesis topic, much of the time dedicated to data collection was spent contacting customer support to solve this issue. Triggered mode on Nexus software was unattainable, and the end solution was to pair the sensors on Delsys EMGworks software and use sync input and output cables connected from our trigger module to our motion capture system to synchronize the initiation and termination of EMG data collection and motion capture simultaneously. Although this worked, the collection frequencies for EMG sensors on EMGworks are not whole numbers, and the selected 2148 Hz frequency was not optimized for Visual 3D data processing. After communicating with associates at Visual 3D, a software update was released, but still did not solve the issue, nor in a timely manner for the completion of the present study. The EMG data collected previously for this study can be used for future researchers to further investigate the primary purpose of this thesis topic and may provide further insight into how fatigue effects the quadriceps and hamstring muscles during running.

In addition to the technology issues faced during the process of initiating this study, the novel COVID-19 virus created many issues with participant recruitment. During the first portion of fall semester, University policies restricted close in-person contact with individuals on school property, and especially so without explicit consent from the University for laboratory data collections. This delay of in-person contact did not allow for initial pilot testing procedures to take place. Further, there was substantial difficulties with recruiting participants due to personal health concerns, and simultaneously due to the delayed recruitment after the time taken to troubleshoot EMG. Of course, if this study were to be continued, substantially more power could be obtained to gather stronger results and better inferences for this study.

Multiple results either approached significance or had considerable effect sizes that suggest changes in those variables may be of interest. Without exhausting the list of the many variables that can be referred to in Tables 1 and 2, knee abduction moment between muscles was significantly different (Figure 9), yet the reason for it is unclear. If this result can be duplicated in the future, this may afford some critical insights into potential injury mechanisms that are known to be caused by differences in knee abduction, and specified to the muscles that, when fatigued, give rise to this potential biomechanical risk factor.

As mentioned earlier, although EMG was not able to be used in this study, it was collected for all participants and could be used for future study. In addition to the fatigue that was done at the knee, future research could also incorporate ankle joint fatigue with a similar approach to independently fatigue the anterior and posterior musculature at the ankle joint and observe the subsequent changes that may occur. Fatigue about the ankle joint has been shown to cause a decrease in dorsiflexion angle at initial contact, and loading rate of impact forces (34,71). Ankle joint fatigue is also one of the main areas of force attenuation, and fatigue at the ankle has a greater impact on forces than fatigue at the knee (71). Including fatigue at the ankle and comparing it to the fatigue protocol in this study may provide some additional insights into how impact and braking forces differ from pre-fatigue values, considering that in the present study, both peak impact forces and braking forces were observed to change after the introduction of fatigue, in contrast to previous findings.

Future research may also benefit from observing changes during the swing phase of running without being limited just to stance. Throughout the different phases of the running cycle, muscular activity of the individual muscles varies, and the loading peaks of the hamstring muscles are greatest during the swing phase (18). Having fatigued the hamstrings independently to the quadriceps, there may be some critical changes from pre-fatigue to post-fatigue that occur during swing as observed in previous studies (16,71). Furthermore, incorporating different speeds can display different levels of performance, muscular activations, kinematics, and kinetics that would provide a more specific array of activity to individuals in sports. Speed-related differences in muscular activity have been previously researched (17,18,82) in athletic populations, and muscular injury tends to follow a positive relationship with increasing speed.

Clinical Significance

Running is a popular method of exercise, and inherent to participation in the majority of sports, but is associated with a multitude of injuries. Whole-body or localized fatigue is considered a risk factor for acute and running overuse injuries (6,34,46,72,79,90,92). The result of many of these injuries stems from errors during training or break down in technique, but is amplified by fatigue (9,15,46,78,92). Literature related to both acute and overuse injuries from running aim to better understand how to improve current preventative and rehabilitative programs associated with better muscle function and coordination in runners. The present study sought to address the gaps in the literature regarding independently fatiguing the hamstring and quadriceps muscles to understand how fatigue affects the individual force-generating capacities and associated compensatory strategies that arise. Our findings showed, primarily, that independently fatiguing the knee flexors and extensors resulted in changes in kinematics and kinetics that differ from previous research that fatigued these muscles simultaneously (71,72). Knee flexor fatigue showed greater change in knee flexion during the stance phase for the two-minute post-fatigue run than extensor fatigue. Vertical impact peak force was observed to increase over time after the introduction of both fatigue protocols. Because some of these compensations have also been observed in whole-body fatigue protocols (5,15,90), fatigue of the knee flexors and extensors likely have key roles in the observed changes in lower extremity kinematics and kinetics during fatigued running. Clinically, these results suggest training emphasized around strengthening musculature about the knee joint, and endurance training to maintain proper running technique upon the onset of fatigue so that acute or overuse injuries may be avoided. These suggestions should be considered as a whole regarding the lower extremity joint musculature, as the findings of this study have shown altered motion about the hip as well.

Limitations

Certain limitations present during this study may have influenced results. Firstly, according to an a priori power analysis (65,71,72), 15 participants were needed to obtain statistical power for this study, however, persistent technological issues that were essential for data collection and processing, as well as the novel COVID-19 pandemic presented substantial difficulties with subject recruitment and significant delays, hence only five participants were recruited. Issues with electromyography (EMG) both significantly delayed participant recruitment, but also ultimately were not able to be included in the final analysis due to further issues with EMG data processing and time constraints. Future research should include EMG data of specified lower extremity muscles to assess the individual role the muscles play in coordinating joint motion under the influence of fatigue while running. Additionally, fatigue level was assessed by estimating of subject's maximal voluntary efforts, which were assumed to be full effort. Under the circumstances where full effort was not given, fatigue level would have been overestimated and may have influenced results. Further, activity history differed between subjects which may have affected their adherence or suitability with the study's procedures, and ultimately with the level of voluntary effort. Finally, treadmill running versus overground running is inherently different and can pose certain changes in the lab that do not fully represent what happens during everyday activity. However, when testing using treadmills compared to overground running, previous literature has confirmed that the difference is small and does not significantly influence performance (95).

Conclusion

The present study analyzed the influence isolated quadriceps or hamstring fatigue had on kinematic and kinetic variables and assess the short-term recovery process following acute fatigue. Findings from this study indicated that individually localized muscle fatigue of knee flexors and extensors affected kinetics to a significant degree at the joint involved in the fatigue protocol, as well as at the hip joint, but showed insignificant kinematic differences. Changes in running mechanics and impact forces were observed to be more substantiated either immediately post-fatigue, or during the post-fatigue run. Few of the factors were observed to show differences during the short-term recovery period when compared to pre-fatigue values.

Though there were non-significant kinematic differences, we suspect that a greater sample size would provide the statistical power that would indicate joint range of motion may be influenced by fatigue of these muscles. Including muscular activation measurements may have provided another angle of perspective to the internal changes that occurred in this study to better explain the differences between muscles that were not apparent with kinematic and kinetic data. Future research should consider including the ankle joint with the type of fatigue protocol included in the present study, as we believe there could be more informative potential with how ground reaction forces change considering the ankle’s role in controlling coordination at the distal lower extremity.

Figures and Tables

	Variable	Muscles Fatigued	Pre	Post	Post-2	Post-12	p-value/Effect Size (η_p^2)		
							Muscle	Time	Muscle*Time
HIP	Hip Extension (°)	Quad	-19.15 (1.34)	-14.51 (0.81)	-17.74 (1.78)	-18.37 (0.85)	0.477 (~0.133)	0.065 (*0.441)	0.361 (~0.123)
		Ham	-16.70 (2.77)	-16.42 (2.55)	-17.41 (1.74)	-15.49 (1.95)			
	Hip flexion @ initial contact (°)	Quad	40.25 (3.08)	38.38 (2.59)	38.12 (2.92)	40.43 (3.56)	0.645 (^0.058)	0.551 (*0.155)	0.38 (*0.219)
		Ham	40.54 (0.88)	38.03 (1.68)	39.63 (2.73)	38.87 (2.22)			
	Hip sagittal plane min velocity (m/s)	Quad	-257.41 (22.72)	-256.07 (27.72)	-270.25 (32.30)	-239.61 (29.95)	0.696 (^0.042)	0.318 (*0.246)	0.623 (*0.227)
		Ham	-247.63 (26.15)	-271.14 (23.07)	-269.43 (19.98)	-253.66 (24.42)			
	Hip sagittal plane max velocity (m/s)	Quad	91.62 (29.73)	48.04 (23.80)	104.82 (49.34)	90.87 (35.21)	0.664 (^0.052)	0.49 (*0.175)	0.357 (*0.228)
		Ham	101.90 (13.59)	92.28 (32.24)	102.06 (32.35)	80.45 (26.15)			
KNEE	Knee sagittal peak flexion (°)	Quad	42.93 (2.90)	38.94 (2.34)	39.79 (2.18)	39.40 (2.25)	0.82 (^0.014)	0.703 (~0.107)	0.718 (*0.249)
		Ham	40.23 (1.69)	39.32 (1.77)	41.23 (2.29)	39.51 (1.77)			
	Knee sagittal flexion @ initial contact (°)	Quad	14.99 (2.45)	13.14 (3.37)	13.50 (3.86)	11.50 (3.41)	0.592 (*0.205)	0.088 (*0.409)	0.456 (~0.102)
		Ham	14.02 (1.83)	12.95 (2.94)	14.62 (3.23)	13.67 (2.80)			
	Knee peak rotation (°)	Quad	4.30 (3.07)	4.57 (3.22)	4.22 (3.05)	4.11 (2.88)	0.693 (^0.043)	0.265 (*0.273)	0.066 (*0.18)
		Ham	2.98 (4.41)	2.49 (4.84)	5.40 (3.71)	2.633 (4.92)			
	Knee rotation @ initial contact (°)	Quad	-4.29 (2.22)	-3.80 (2.64)	-4.93 (3.58)	-3.85 (2.51)	0.941 (0.002)	0.530 (*0.162)	0.312 (*0.439)
		Ham	-2.68 (1.73)	-2.20 (3.00)	-4.00 (3.14)	-5.27 (2.72)			
	Knee frontal abduction @ initial contact (°)	Quad	-6.06 (1.56)	-6.42 (1.41)	-6.57 (1.63)	-6.46 (1.47)	0.849 (*0.175)	0.579 (*0.146)	0.051 (*0.334)
		Ham	-5.22 (1.85)	-4.81 (1.61)	-4.67 (1.63)	-3.99 (1.82)			
	Knee sagittal plane peak velocity (m/s)	Quad	500.10 (16.07)	492.64 (32.22)	491.97 (38.67)	494.07 (29.26)	0.664 (^0.052)	0.494 (*0.175)	0.357 (~0.062)
		Ham	496.19 (15.13)	501.07 (19.41)	475.86 (16.75)	482.77 (19.79)			
	Knee abduction peak velocity (m/s)	Quad	101.01 (3.13)	94.56 (6.77)	118.83 (3.35)	102.80 (7.56)	0.799 (^0.018)	0.87 (^0.056)	0.85 (*0.24)
		Ham	105.94 (14.47)	122.70 (18.03)	123.19 (10.87)	121.15 (10.84)			
	Knee transverse plane peak velocity (m/s)	Quad	258.16 (29.29)	265.89 (25.41)	295.85 (20.01)	248.89 (27.98)	0.313 (*0.25)	0.093 (*0.402)	0.331 (*0.178)
		Ham	260.87 (30.95)	266.04 (37.48)	296.91 (56.07)	287.13 (33.76)			

Table 1. Kinematic variables for the hip and knee. Values expressed as mean (SD). Stance phase occurs from initial contact to toe-off.
Sagittal motion – Flexion (+); Frontal motion – Adduction (+); Transverse motion – Internal rotation (+)
Abbreviations: Pre: Pre-fatigue, Post: Immediate post-fatigue, Post-2: 2-min post-fatigue, Post-12: 12-min post-fatigue
Bold indicates significance ($p<0.05$)
Effect size calculated as Partial eta squared (η_p^2)
*Large effect size (≥0.14); ~Medium effect size (0.06); ^Small effect size (0.01)

	Variable	Muscles fatigued	Pre	Post	Post-2	Post-12	p-value/ Effect Size (η_p^2)		
							Muscle	Time	Muscle*Time
	Peak vertical GRF (BW)	Quad	2.789 (0.093)	2.459 (0.096)	2.622 (0.068)	2.647 (0.070)	0.874 (0.007)	0.089 (*0.407)	**0.009** (0.603)
		Ham	2.622 (0.070)	2.539 (0.100)	2.676 (0.053)	2.644 (0.029)			
	Breaking Min (BW)	Quad	-0.41 (0.014)	-0.389 (0.005)	-0.452 (0.021)	-0.434 (0.024)	0.339 (*0.228)	**0.003** (*0.677)	0.98 (0.015)
		Ham	1.859 (0.361)	-0.385 (0.020)	-0.444 (0.025)	-0.426 (0.016)			
HIP	Hip max extension moment (Nm/kg)	Quad	1.591 (0.122)	2.066 (0.300)	1.659 (0.169)	1.569 (0.212)	0.645 (^0.058)	0.20 (*0.155)	0.38 (0.116)
		Ham	3.400 (0.493)	1.625 (0.193)	1.637 (0.272)	1.465 (0.149)			
	Hip power max (Watts/kg)	Quad	2.765 (0.834)	3.161 (0.655)	3.458 (0.559)	2.121 (0.521)	0.368 (*0.205)	0.069 (*0.311)	0.672 (0.189)
		Ham	4.009 (0.441)	3.242 (0.845)	2.487 (0.698)	2.336 (0.934)			
KNEE	Knee extension moment (Nm/kg)	Quad	3.183 (0.388)	3.209 (0.302)	3.823 (0.261)	3.864 (0.332)	**0.032** (*0.723)	**0.008** (*0.61)	0.206 (0.307)
		Ham	1.023 (0.189)	3.096 (0.272)	3.367 (0.245)	3.304 (0.372)			
	Knee abduction moment (Nm/kg)	Quad	2.464 (0.188)	0.893 (0.131)	1.067 (0.168)	1.033 (0.188)	**0.001** (*0.96)	0.303 (*0.253)	0.670 (0.117)
		Ham	-19.146 (1.336)	2.481 (0.266)	2.513 (0.166)	2.572 (0.229)			
	Knee power absorption (Watts/kg)	Quad	-16.704 (2.773)	-14.509 (0.806)	-17.741 (1.779)	-18.367 (0.847)	0.783 (^0.021)	0.437 (*0.196)	0.485 (0.227)
		Ham	11.324 (1.742)	-16.417 (2.554)	-17.410 (1.738)	-15.490 (1.951)			
	Knee power propulsion (Watts/kg)	Quad	8.573 (1.286)	6.926 (0.904)	9.914 (0.967)	9.335 (1.340)	0.328 (*0.236)	**0.023** (*0.535)	**0.050** (0.466)
		Ham	2.789 (0.093)	7.773 (0.409)	8.788 (0.765)	8.451 (1.58)			

Table 2. Kinetic force variables and hip, knee, and ankle joint kinetic variables. Values expressed as mean (SD). Moments are peak internal moments (Nm/kg) during the landing phase (initial contact to max knee flexion angle)

Abbreviations: Pre: Pre-fatigue, Post: Immediate post-fatigue, Post-2: 2-min post-fatigue, Post-12: 12-min post-fatigue;
GRF: ground reaction force; BW: Body weight; Nm/kg: Newton-meter per kilogram

Bold indicates significance ($p<0.05$)

Effect size calculated as Partial eta squared (η_p^2)

*Large effect size (≥0.14); ~Medium effect size (0.06); ^Small effect size (0.01)

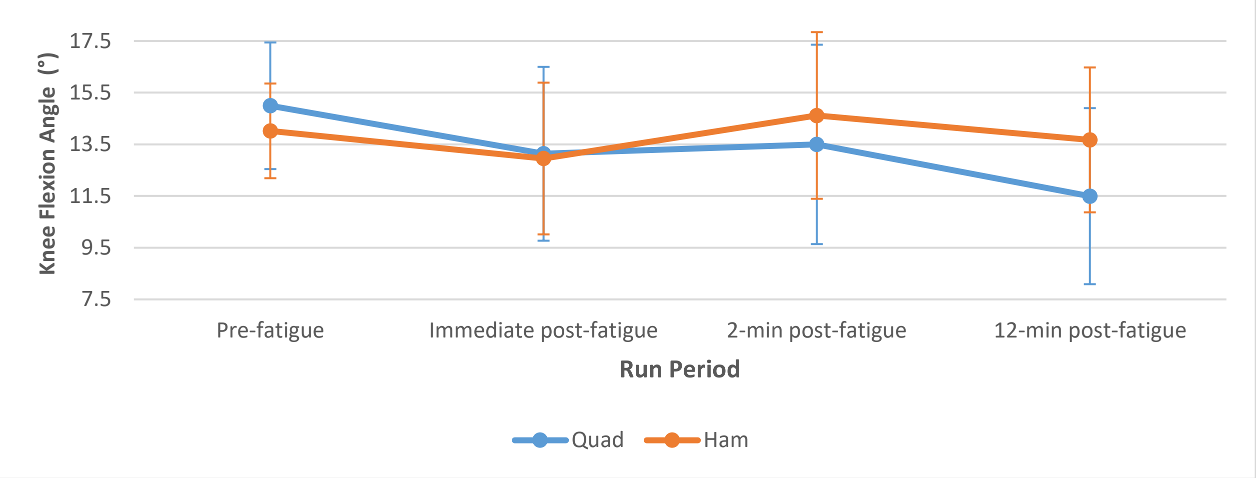

Figure 1. Mean differences in knee flexion angle at initial contact during stance as a function of individualized fatigue of knee flexors and extensors. Knee flexion differences approached significance for time (p=0.088; η_p^2=0.441)

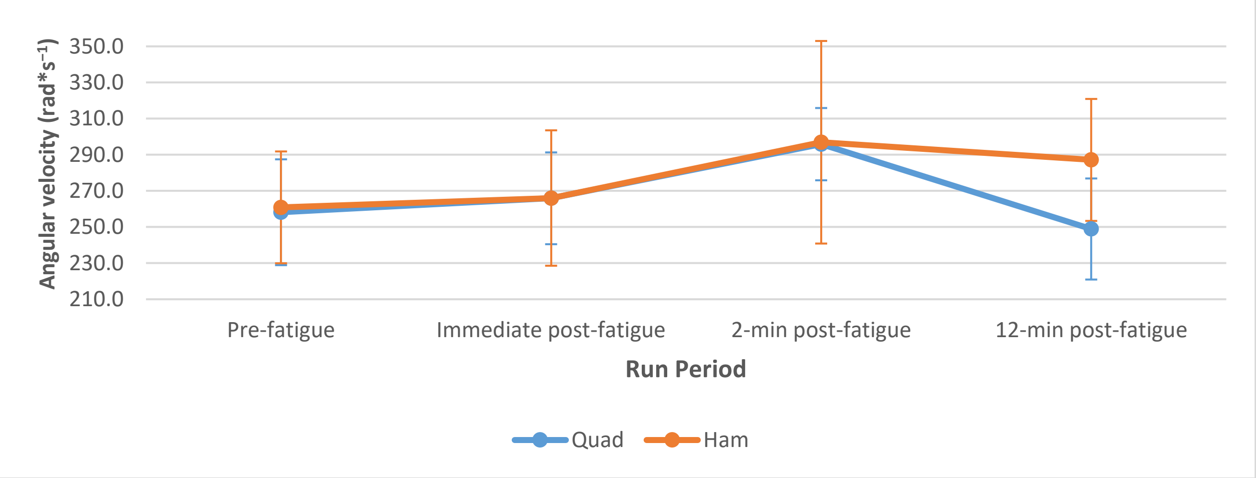

Figure 2. Mean differences in knee transverse plane peak velocity approached significance for time (p=0.093; η_p^2=0.402). Knee flexor muscles exhibited greater recovery than knee extensors.

rad▪s^{-1}= radians per second

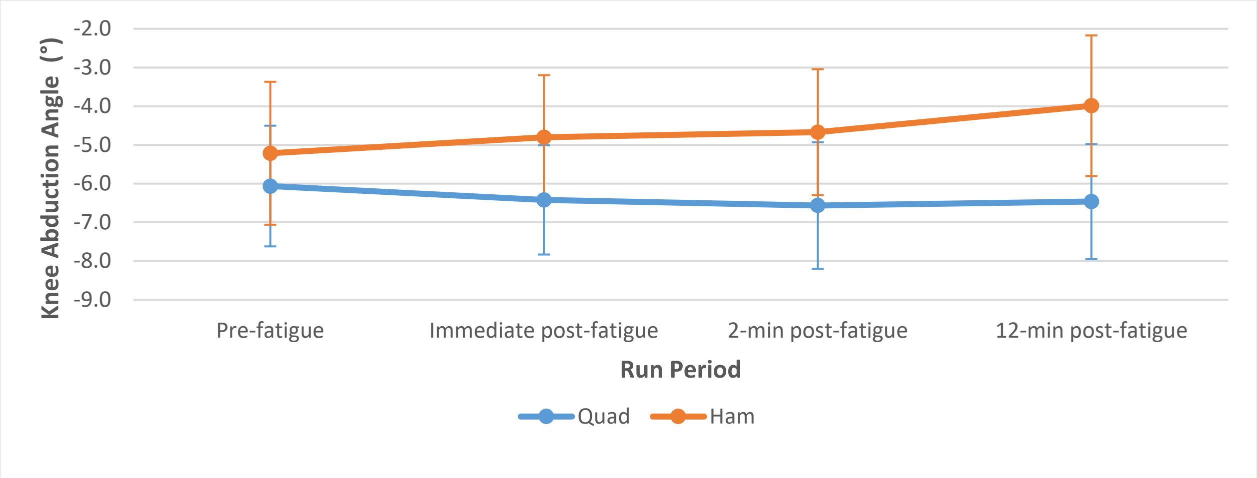

Figure 3. Mean differences in knee abduction angle at initial contact showed little change over time but was substantially different between knee flexors and extensors.

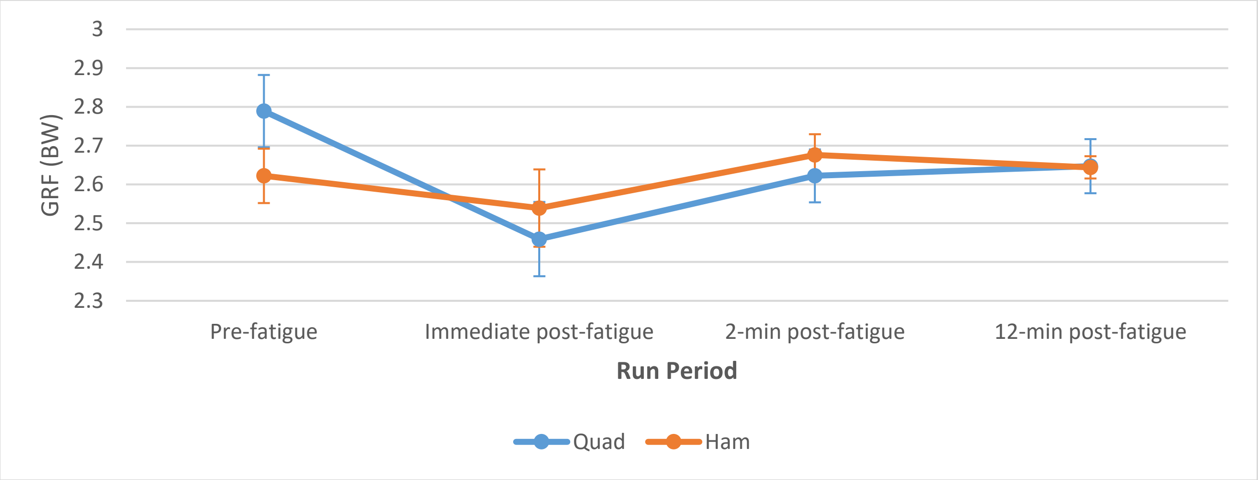

Figure 4. Peak vertical impact peak force showed a significant decline post-fatigue of knee extensors followed by a gradual increase in GRF towards pre-fatigue level.
GRF = ground reaction force; BW = bodyweight

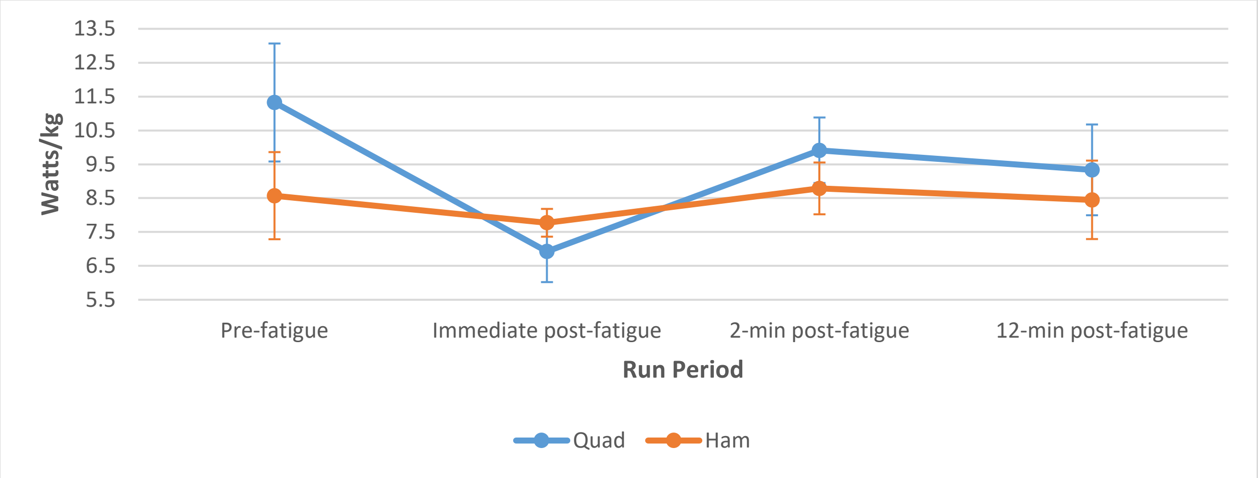

Figure 5. Maximum propulsive knee power significantly declined (p=0.023; η_p^2=0.535) from pre- to post-fatigue of knee extensors followed by increased knee power propulsion during the initial fatigued run.

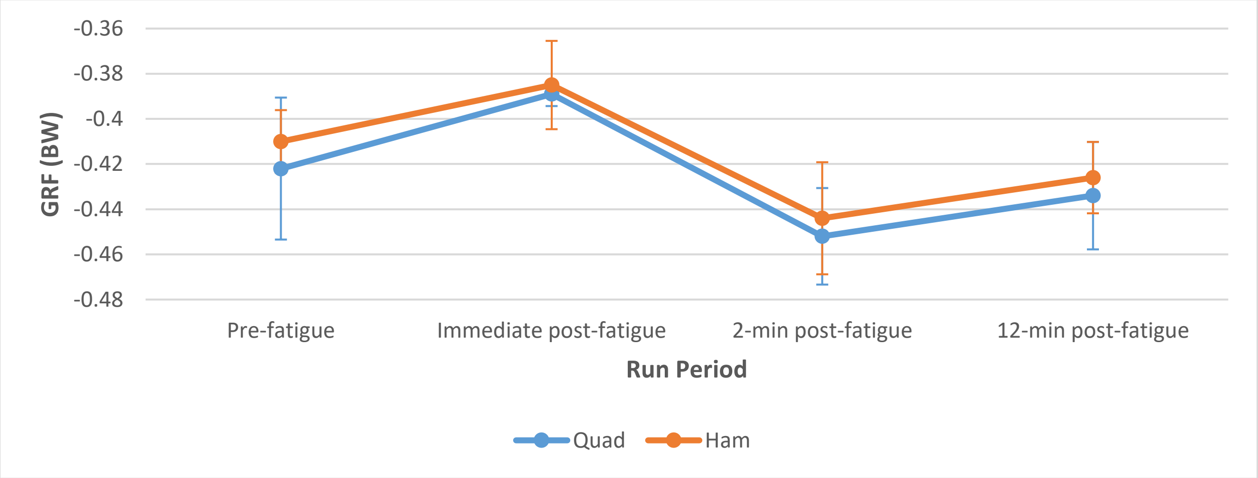

Figure 6. Maximum horizontal braking force showed similar trends in mean differences for both knee flexors and extensors over time. Both knee flexors and extensors exhibited less braking force immediate post-fatigue, increased during the fatigued run and began recovery back to pre-fatigue level.

GRF = ground reaction force; BW = bodyweight

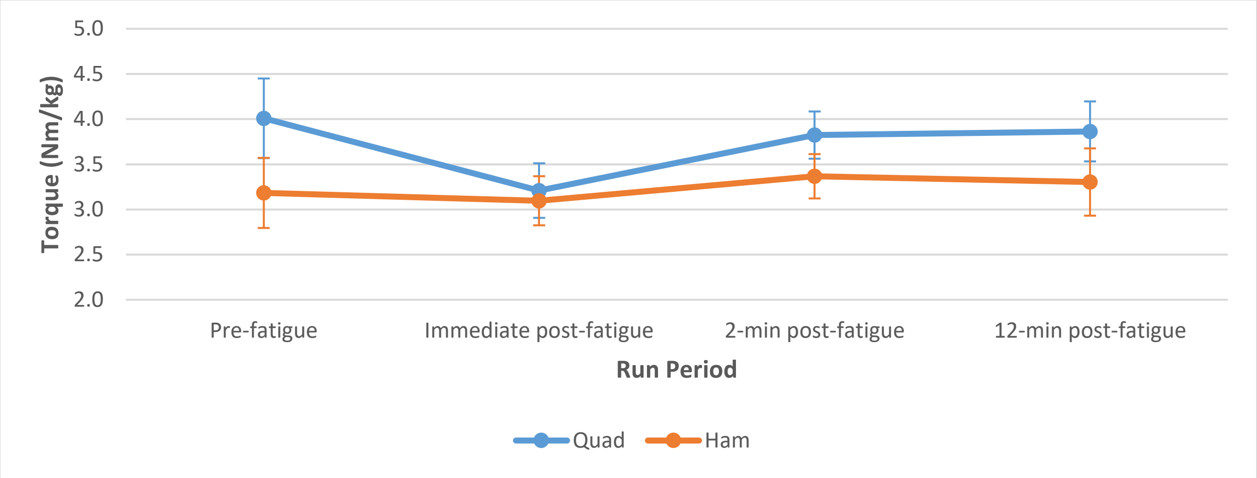

Figure 7. Mean differences in maximum knee extension moment was significantly decreased immediate post-fatigue of knee extensors and returned back to pre-fatigue levels during the post-fatigue run.

Nm/kg = newton meters per kilogram

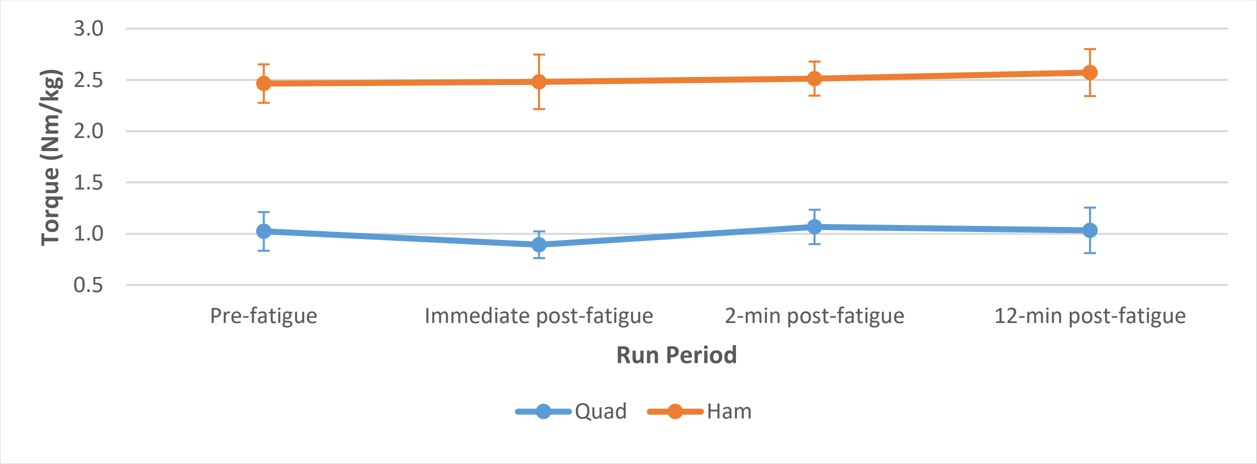

Figure 8. Mean differences in maximum knee abduction moment were substantially different between the knee flexors and extensors. Small differences were observed as a result of fatigue, but between muscle differences were significantly different (p=0.001; η_p^2=0.96).

Nm/kg = newton meters per kilogram

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Appendix A: Health History Questionnaire

IRB Approval #: 1674565-3

Health/Activity Information
Biomechanics Laboratory - Ball State University

Subject ID __________________
Gender: Male ____ Female ____
Age: ________
Emergency contact: ____
Phone#______________________________________

1. Do you have any health conditions that limit you in performing physical activity? Y / N
If YES, please explain:
____
____
____

2. Have you ever had any kind of knee ligament injury to any degree? Y / N
If YES, please explain:
____
____
____

3. Do you currently have any type of lower extremity injury or pain? Y / N
If YES, please explain:
____
____
____
____

4. Have you ever been diagnosed as having any of the following conditions? Y / N
If YES, please explain:
Joint replacement ____
Uncorrected visual problems ____
Other health problem? ____

5. Do you currently suffer any of the following symptoms in your legs or feet?
Numbness ____ Tingling ____ Arthritis ____ Swelling ____

6. Do you currently have any medical conditions for which you see a physician regularly? Y / N

If YES, please describe the condition(s):

____

____

7. Have you required emergency medical care or hospitalization in the last three years? Y / N

If YES, please list when this occurred and briefly explain why.

____

____

8. How would you describe your health?

____ Excellent ____ Very good ____ Good ____ Fair ____ Poor

<u>Physical Activity</u>

1. How many days per week do you exercise?

One ___ Two ___ Three ___ Four ___ Five ___ Six ___ Seven ___

2. How many minutes, on average, do you exercise per day? ____________________

3. How long have you been exercising regularly? _______________

4. When did you last exercise? ________________________

5. How many days per week do you run?

None ___ One ___ Two ___ Three ___ Four ___ Five ___ Six ___ Seven ___

6. How many minutes do you run for when you run? ______________

7. How long have you been running for exercise? ______________

8. What kind of running do you do? (e.g., short run < 5 mi, long run >5 mi, sprinting)

____

Appendix B: Informed Consent

Informed Consent

"The Effect of Localized Muscular Fatigue on Lower Body Running Mechanics and Muscular Activation During Treadmill Running"

Who is conducting the study?

This is a scientific research study conducted by Samuel Rosario and Dr. Clark Dickin in the Biomechanics Laboratory at Ball State University.

What is the purpose of this study?

The purpose of the study is to assess the effect of localized fatigue on lower body compensatory strategies that may affect running performance.

What criteria must be met for me to participate in this study?

‣ Refrain from vigorous exercise 24 hours prior to participation

‣ Recreationally active (30 min activity 3x/week), or runners who run at least 15 miles/week, adult males and females between the ages of 18-25 years

‣ Not be recovering from any acute or chronic injuries of the lower extremities

> - If recovered, must be medically cleared and able to perform equivalent to pre-injury level (e.g., training volume, running form not impaired by injury, no noticeable decrease in strength) at least 1 month prior.

‣ Not have any chronic ailments or injuries that would inhibit them from performing knee flexion/extension

‣ Examples of exclusion include a recent or chronic history of lower extremity sprain/strains, fractures, tendonitis, and peripheral neuropathies in the lower extremities

Where is the study going to take place and how long will it last?

The study will take place in the Ball State University Biomechanics Laboratory, HP 309 & 311. Your participation in the study will consist of two visits to the Biomechanics Laboratory. On each visit you will be asked to come to the laboratory for approximately 90-120 minutes. The total amount of time you will be asked to volunteer for this study is approximately three to four hours over the course of two days. The time between the two days will be ~7-10 days.

What will I be asked to do?

You will be informed of the protocol and asked to read and sign the Informed Consent document. You will also be asked to fill out a standard Health Assessment Questionnaire reporting things such as any known disease and any medications you are currently taking, as well as a Health Assessment Questionnaire catered towards the novel COVID-19 virus. The initial questionnaires will be completed virtually (e.g., phone, zoom) and following the completion of the forms you will be informed if you are eligible for the in-person data collection.

The in-person testing will consist of two testing sessions, you will be asked to wear a pair of compression shorts and sleeveless top and face mask. Measurements of your height, weight, and lengths of lower-extremity segments will be taken. We will then attach 7 passive surface electrodes that will measures muscle activity, to your right and left legs (14 total). These electrodes will monitor the overall muscle activity during testing. Individual reflective markers will also be attached to various anatomical landmarks on the body (e.g., knee, ankle, mid-thigh).

Based on random assignment you will be assigned to either a quadriceps or hamstrings group.

You will then step onto the treadmill and asked to warm-up for 5-minutes at a self-selected pace. You will be running on the treadmill with no incline to simulate level-ground running. If you do not reach a speed of 3.61 m/s (roughly 8 mph), you will be given 30-seconds to run at this pace for acclimation purposes. A 1-minute rest will be taken before the pre-fatigue run. After resting, you will run at 3.61 m/s for 2 minutes for the pre-fatigue running trial. Following the run a series of knee extension or flexion contractions using maximal effort will be performed followed by a 1-minute rest before starting the fatigue protocol.

The fatigue protocol will consist of continuous shortening and lengthening knee extension or flexion efforts (depending on your assigned group) at 60°/s. You will be given verbal encouragement while participating in the fatigue protocol. You will be asked to contract until you have reached your fatigue level, at which time you will be given a 1-minute rest period and then asked to complete the fatiguing contractions until fatigue 2 more times. Once fatigued, you will be prepared for the post-fatigue run.

For the post-fatigue run, you will run at 3.61 m/s for 2-minutes while data is being collected. After the 2-minute run, you will be given an additional 8-minutes to rest (total of 12-minutes after the end of the fatigue contractions) before running for a final 2-minutes at 3.61 m/s.

What are the possible risks and discomforts?

As a participant in this study there are some potential minor discomforts. It is possible you might experience localized muscular fatigue and soreness toward the end of the test session, or on the following day. It is expected that this soreness will lessen and disappear over the next few days. Additionally, as in any sport or exercise, there is a small possibility that you could sprain a ligament, strain a muscle, or experience other mild, moderate, or severe injuries.

Do I have to take part in this study and will I benefit from it?

Your participation in this study is completely voluntary. You are free to withdraw from the study at any time for any reason without penalty or prejudice from any member of the research team. The results from your participation in this study has the potential to benefit society in terms of helping to reduce injuries from fatigue while running. Upon completion of the study, you will have an equal opportunity to receive one of two $25.00 Tango gift cards, and a free gait analysis. Please feel free to ask questions to clarify any of this form before signing it.

Who will see the information that I give?

The data collected during this study will remain confidential. If you are chosen as one of the two participants for the $25.00 Tango gift card, contact information for receiving a gift card will be shared with Tango. You will receive a generic email from Tango, not the principal investigator, on how to redeem the gift card. You will not be identified in any way in subsequent publication or presentation of this research. Only members of the research team will have access to the data. All written records will be stored in a locked file cabinet in a locked room. All electronic data will be stored on a password protected computer and will be kept indefinitely for potential future research and publication purposes. If you withdraw, your data will be deleted. You will be identified on study documents and in electronic files by a study acronym (e.g., FR_001) to help retain your confidentiality. By signing this form, however, you allow the research investigators to make your records available to the Office of Research Integrity at Ball State University and regulatory agencies as required by law.

What happens if I get hurt or sick during the study?

It is understood that in the unlikely event of an injury or illness of any kind as a result of your participation in this research project that Ball State University, its agents and employees will assume whatever responsibility is required by law. In the event that you should require it, emergency care will be provided to you at your expense. If any injury or illness occurs in the course of your participation in this research project, please notify Dr. Clark Dickin or the Biomechanics Laboratory at (765) 285-5178.

What if I have questions?

If you have any questions concerning your involvement in this study, you may contact the principal investigator Samuel Rosario at sdrosario@bsu.edu, Dr. Dickin, or the Biomechanics Laboratory at (765) 283-5178 at any time.

For questions about your rights as a research subject, please contact:

Office of Research Integrity
Ball State University
Muncie, IN 47306
Phone: (765) 285-5052 E-mail: orihelp@bsu.edu

Consent

I, ___________________________________, agree to participate in this study "The Effect of Localized Muscular Fatigue on Lower Body Running Mechanics and Muscular Activation During Treadmill Running". I have had the study explained to me and my questions have been answered to my satisfaction. I have read the description and gave my consent to participate. I understand that I can withdraw my consent at any time during the study if I feel uncomfortable. I understand that I will receive a copy of this informed consent form for my own reference. I understand that my participation in this study depends on my age and activity level and that I may not be selected if I do not meet the necessary criteria. To the best of my knowledge, I meet the inclusion criteria for participation in this study.

Participant Signature Date

____

Participant Name Printed

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Signature of Investigator

____

Principal Investigator	**Advisor**
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