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Altering a Runner's Foot strike using a Modified Elliptical Trainer

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A thesis submitted in partial fulfillment of the requirements for the degree of
Master of Science at Virginia Commonwealth University

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Abstract

ALTERING A RUNNERS FOOT STRIKE PATTERN USING A MODIFIED ELLIPTICAL TRAINER

By Daniel Stephen Shull, B.S. Biomedical Engineering

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science Biomedical Engineering at Virginia Commonwealth University.

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One possible solution to common running related injuries is to transition runners from a rearfoot strike during initial contact to a midfoot strike. Natural rearfoot strike runners were studied to see if a modified elliptical trainer could be used to alter their running pattern to that of a midfoot strike runner. Their results were compared to subjects who ran on a non-modified elliptical trainer. After training on the modified elliptical trainer, subjects demonstrated a decrease in foot angle at initial contact when attempting to run with a midfoot strike. Training did not affect all kinetic metrics or stride frequency. However, the kinematic change suggests that there may be an impact on running energetics. Training on the modified elliptical trainer resulted in improved midfoot strike kinematics in natural rearstrike runners when they attempted run in a midfoot strike pattern.

Chapter 1: Introduction

Running is an activity that humans have been doing for millions of years. Some people run to get exercise, some run for the fun of it, and others run for survival. No matter what the purpose, there is one common factor that is constant among runners: injuries. The injury rate among runners varies between different research studies, some stating that 79%[1] of runners experience an injury annually while others say injury rates vary between 30%-75%[2]. This is most likely because of the different ways injury can be defined or the different populations of subjects used in each of the studies. No matter the reasons for the variability, it cannot be argued that runners do experience injuries. These injuries can be separated into three different categories: structure, dosage, and mechanics. Structure refers to injuries that are caused by the genetic structure of the runner, including but not limited to foot type (i.e. high arch vs. low arch). Injuries related to dosage are associated with the amount of time spent running and how much time is allowed for the body to recover between running sessions. Injuries that fall into these categories can be managed in several ways. For example, providing more shoe support or modifying the intensity of the running schedule can decrease injury rates[3,4]. Mechanics is a category of injuries related to running technique. These injuries are often more difficult to manage than structure or dosage since they require the modification of temporal and spatial characteristics of a runner's technique. This study will focus on modifying a runner's mechanics, specifically the initial contact foot strike pattern, to better manage injuries in runners that are caused by less than ideal running mechanics.

Normal Gait Pattern

In bipedal locomotion, the act of placing one foot in front of the other is defined as a gait cycle. One cycle is described as the time from one foot strike to a subsequent foot strike of that same foot. This cycle is equated to 100% and is also termed a stride. The length and frequency of a person's stride can differ based on many factors including, as described later in further detail, the type of foot strike pattern used. Stride can sometimes be mistaken for step since step is the length between the initial contacts of two different limbs[5]. The stride consists of two phases, stance and swing. The stance phase is the period of time when the foot is in contact with the ground and is typically 60% of the gait cycle. The swing phase is when the foot is not in contact (while advancing to the next contact). This is typically 40% of the gait cycle. Each of these phases can be further subdivided. Stance can be divided into initial contact, loading response, mid-stance, terminal stance, and toe off. Additionally, descriptions of initial double stance, single limb stance, and terminal double stance describe the relationship of the stance leg with contralateral leg movements. The swing phase can also be divided into initial swing, mid-swing, and terminal swing. Together these two phases represent a normal gait cycle and occur in the following order: initial contact with the ground occurs resulting in initial double stance. Single limb stance begins as the opposite foot is lifted off the ground and only one foot remains on the ground. Once the opposite foot has again made contact with the ground, terminal double stance begins and continues until the foot starts to lift off the ground, (also referred to as toe-off) and start the swing phase of the gait cycle. The movement of lifting the foot off the ground is the initial swing phase and continues until the foot has traveled past the opposite foot, which is still in contact with the ground, and becomes mid-swing. Terminal swing is when the foot has again made contact with the ground[5].

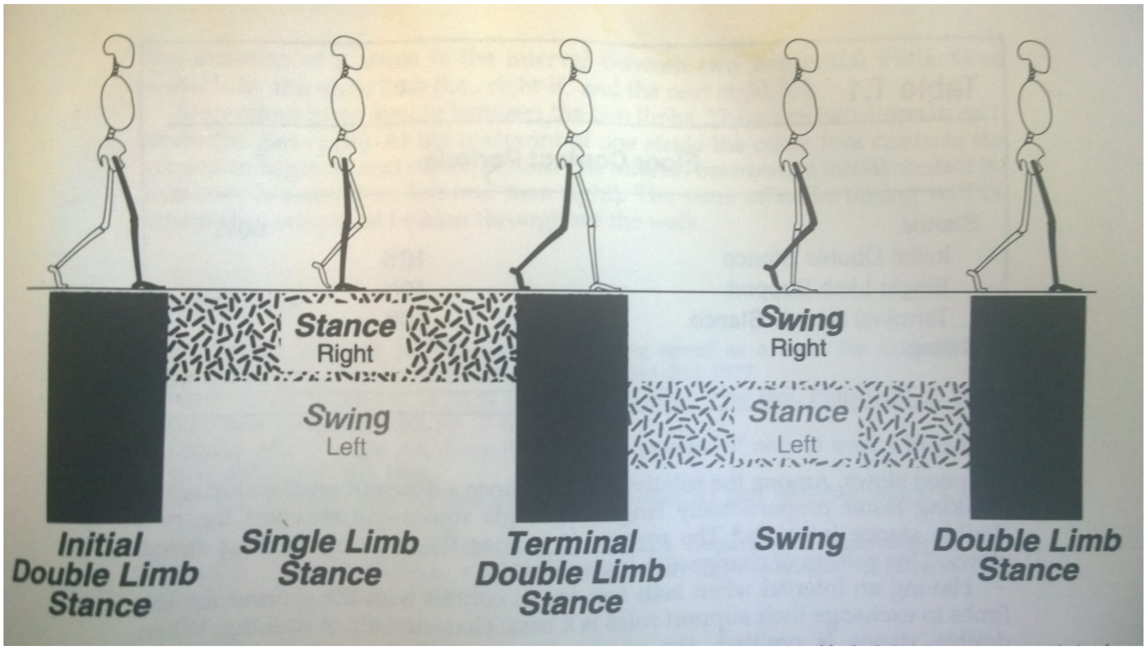


Figure1-1: Normal walking gait cycle as illustrated by Perry[5]. (Picture credited to Perry, 1992)

During running a similar pattern exists with some exceptions. The primary difference is the loss of double stance. It is replaced instead by an interval where both feet are not in contact with the ground creating consecutive single limb stance phases with a flight phase in between. As a result, greater peak loads are seen at initial contact during running when compared to walking. The double limb support during walking allows the loads to be distributed between both legs during transitions from side to side. During running, the load is larger, more impulse like, and is only distributed across one leg. These greater peak loads in running are thought to be one of the contributors of overuse running injuries and is why researchers have studied different methods to decrease them. One of these methods, and the focus of this study, is through altering a runner's foot strike.

Foot strike Patterns

Running injuries and the focus on "good" running form and technique has increased interest in the way runners strike the ground. There are three different patterns that have emerged as a result. They are rearfoot striking (RFS) where the heel strikes the ground first, midfoot striking (MFS) where the heel and ball of the foot strike the ground simultaneously, and forefoot striking (FFS) where the ball of the foot strikes the ground first[6]. Of the three foot strike patterns, studies have found that the majority of runners run with a RFS (from 75%-95%) with MFS (about 4%-24%) and FFS (about 1%-2%) far behind[7,8,9]. There is some consensus that this is due in part to running shoe designs. Running shoes have a large amount of cushioning and elastic materials in the heel which in turn has made RFS more favorable[10,11]. One of the variables that researchers use to determine the type of foot strike a runner uses is measuring the foot angle with respect to the horizontal at initial contact (FIC). Defining dorsiflexion as positive, RFS runners have a positive and greater FIC than MFS runners who are expected to have a FIC of zero. FFS runners are expected to have a negative FIC since they are plantar flexing when contact with the ground is made[6].

Studies have shown that RFS has produced an increased vertical average loading rate (VALR) as well as vertical instantaneous loading rate (VILR) in comparison to subjects running with a MFS or FFS[11,12,13,14]. Researchers believe that increased loading rates are contributing to running-related injuires[15,16]. This had led some to believe that switching to MFS or FFS is the answer because unlike RFS which requires the rigid skeletal system to absorb the impact force at initial contact, MFS and FFS cause the muscles and tendons to absorb the load and offload the joints. While this change of offloading the joints with the muscles and tendons can cause other injuries, including calf strains and Achilles tendinopathy, these are usually a result of runners transitioning too quickly between running styles and can be avoided through more controlled transitions and strengthening exercises[17].

There is much talk and research about barefoot running versus running with shoes, also referred to as shod running. This was not the focus of the research so details on the differences will not be discussed; however, one of the negative aspects of running with modern shoes that have cushioned heels is that it promotes RFS and reduces proprioception. It has also been argued that the way the shoes are made, stiffer soles and high arch supports, may cause the feet to become weaker, contributing to excessive pronation during the loading phase of gait leading to injury[11].

Methods in Gait Retraining

Gait retraining is not something that is novel. It is something that has been researched and studied as early as the 1970s. While the different methods and purposes have changed, the goal has been the same: what is the best method(s) to retrain gait pattern? Many of these methods have included some form of feedback including but not limited to verbal, visual, and auditory. A couple of them have included joint motion and angles through electromyogram (EMG) feedback and goniometers[18,19,20,21]. Others have included auditory feedback to help retrain a subject’s gait including a study that altered gait patterns through a sensor that would beep every time the subject had their foot on the treadmill for longer than 80% of the gait cycle. This would inform the subject that they needed to pick up their foot earlier[22]. These studies have shown positive results in altering a person’s gait.

Previous studies all included subjects who were relearning how to walk or had a neurological disorder. This study, however, is interested in running. The difficulty in retraining a person to run, as well as walk, is that the motor pattern being altered has been reinforced over many gait cycles. Runners on average strike the ground around 600-625 times per kilometer[11,17]. Despite this difficulty, there have been successful studies that have altered the running mechanics of runners. A study in 1989 looked at modifying runners gait through verbal feedback during training as well as visual feedback after training from a video. The group that received the feedback, in comparison to the control group that received no feedback, showed much improvement in the desired mechanics that were being taught proving that runners can be taught to alter their running mechanics through gait training[23].

Another form of feedback that became popular more recently is that of real-time feedback, or feedback that is given to subjects immediately. This stems from a concept referred to as “knowledge of results” (KR)[24]. KR is the information given to a subject during an experiment on performance success. This data can then be used by the subject to perform better on the next trial by correcting any errors that may have occurred in the previous trial. As Winstein points out, KR in motor learning is best utilized and has shown the best results in motor learning retention when instantaneous KR is given along with gradual feedback removal. The gradual removal of the feedback allows for subjects to receive the information necessary to change their motor pattern, but also does not allow them to become dependent on it[24]. There have been many studies that have used this concept of real-time feedback to help subjects change and maintain a desired running mechanic. Two of these studies focused on the acceleration of the tibia and vertical force loading rates[25,26]. They used a uniaxial accelerometer taped to the anteromedial side of the tibia to measure the acceleration of the tibia, and force transducers incorporated with a treadmill to measure the ground reaction forces. Visual real-time feedback of the tibial acceleration was given to the subject on a monitor while they ran on the treadmill. They were not given any advice on how to modify their gait, only to decrease their tibial positive peak acceleration below 50% of its current mean. One study only had subjects run for one session[25], while the other had subjects complete multiple sessions, linearly decreasing the amount of feedback after the fourth session[26].

Another study also used visual feedback, but instead focused on retraining the gait of subjects who had bilateral knee pain through measuring their hip adduction angle[27]. Measurements were made by a marker placement device and they were displayed on a monitor in front of the subject in real-time. The subjects were instructed to keep their hip adduction within a grey shaded region and as close to the line as possible, representing ±1 SD of normal hip adduction. They used the same model as Crowell et al. for the amount of sessions and amount of feedback given in each session[26]. Through this study, the subjects reported that they had a dramatic decrease in knee pain and there was a decrease in hip adduction, letting them conclude that learning had occurred.

In addition to visual feedback, researchers have also used audible feedback for gait retraining. Willy et al. describes gait retraining that includes an audible metronome to increase subject’s stride frequency in addition to using verbal instruction and subjects watching themselves in a mirror to help change hip mechanics and ultimately decrease patellofemoral pain[28].

This study is focusing on altering the foot strike pattern specifically rather than looking at other parameters. One example described in Cheung et al. also focuses on this[29]. They included an audible buzzer in the shoe under the calcaneus that buzzed whenever the subject landed on their heel. The goal of the study was for the subjects to shorten their stride and transition out of a RFS technique to help treat their patellofemoral pain. The amount of audible feedback was decreased between each session and a follow-up was done 3 months later to test if learning had occurred. This study was successful in getting subjects to learn as well as decrease their patellofemoral pain.

Foot strike alteration has also helped patients with other conditions. Chronic exertional compartment syndrome (CECS), a muscle and nerve condition that causes pain, swelling and sometimes muscle disability in the legs, is believed to be exercise-induced especially in situations where there is repetitive impact. In patients who develop this condition while running, the researcher Diebel believed he could treat this condition by decreasing the running impact forces in these runners through transition to a forefoot strike[30]. They had subjects diagnosed with CECS undergo training for 6-weeks that included verbal instruction, running drills, increase in stride frequency through metronome feedback, video recording, and barefoot running to eliminate the heel strike. Subjects were successfully able to transition to forefoot striking, but more importantly pain and compartmental pressures were successfully decreased as a result of this training.

Motor Control

When trying to understand how the gait of an individual can be retrained, it is important to understand some of the different theories of motor control. The main differences between the many motor control theories relates to the roles of the central and environmental features of the control system. The two theories that are focused on here are the Motor Program theory and the Dynamic Pattern theory. Motor Program theory is currently the predominate theory in motor control saying motor control is managed by the central nervous system through motor programs that organize, initiate, and execute desired movements[31,32]. The process in which this occurs can be simplified into four categories of neural interactions: motivation, ideation, programming, and execution. Of these four categories, programming and execution are most relevant to motor behavior. Motivation is initiated by emotional or behavioral needs and is then transformed into an idea. The programming neural component is what allows the desired movement to be converted from an idea into the executed movement with the proper strength and pattern. This programming neural output is referred to as the central command. The central command signal is sent to lower neural centers, including the brainstem and spinal cord, so the desired movement can be executed[31,32].

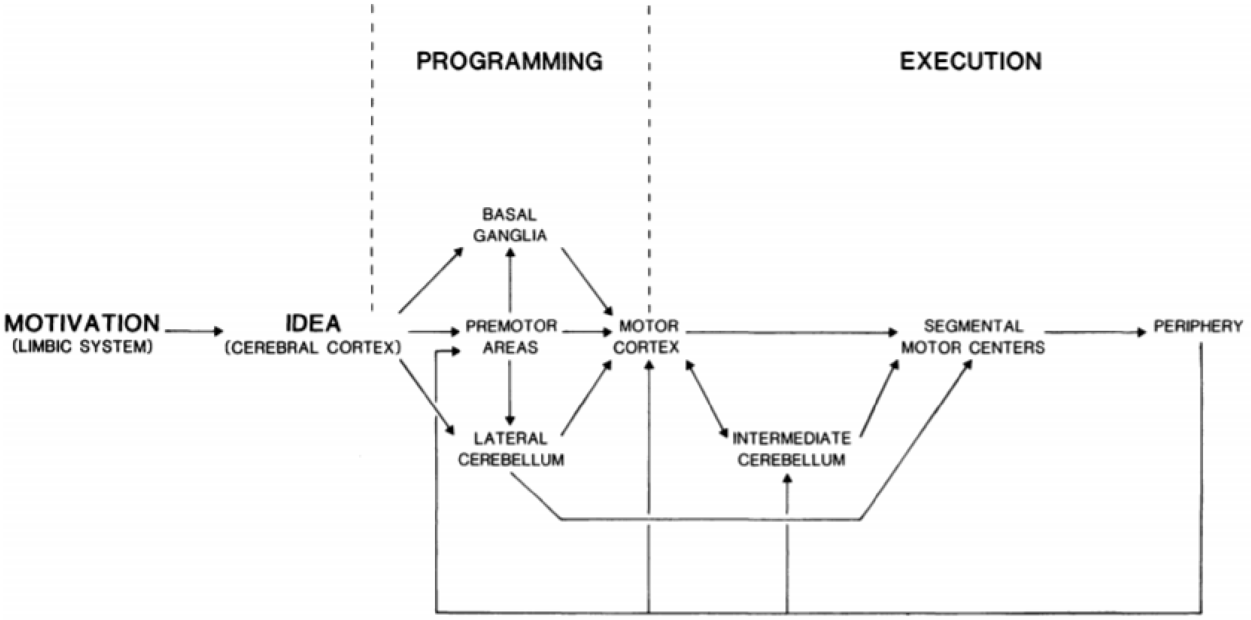


Figure 1-2: The four major neural interactions involved in motor control (Picture credited to Cheney[31]).

Movement execution is not only controlled by this central command signal, but it can also be modified as a result of feedback from sensory receptors. However, not all movements require this feedback in order for this movement to be executed. The distinction is made by labelling movement control as either open-loop or closed-loop. If the motor program contains all the information needed to carry out the action, meaning it is entirely controlled by the central command, the movement operates under open-loop control. On the other hand, if the movement is being continually guided by sensory feedback signals that are evaluating the accuracy of the desired movement, then the movement is being controlled through closed-loop control. In Motor Program theory, feedback is received by the central command to inform it what movement command needs to be sent. The desired pre-programmed movement command is chosen and sent to the specified muscles to carry out the movement. These pre-programmed movements can be modified to yield various response outcomes, but the framework of the movement stays consistent[32].

A more recent motor theory captained by Scott Kelso is Dynamic Pattern theory which speaks for nonlinear changes in motor behavior rather than linear changes as defined in Motor Program theory. Rather than having structured motor programs “hard-wired” into the central nervous system, Dynamic Pattern theory states that movements are instead “softly-assembled” into the central nervous system[33,34]. Explained more succinctly, a movement pattern output is dependent on ever-changing constraints that are placed upon the system. To accommodate for these changes, components of the system controlled by higher brain centers and the periphery “self-organize” themselves, not because they were commanded to by the central nervous system, to produce the desired movement. A constraint is defined as any variable that is related to the completion of the task or movement. These can be structural, environmental, or task specific. Any time there is a change in one of these constraints the system reorganizes itself so it can carry out the task. If the movement needed has not previously been learned, the attempted movement will initially be closer to an already learned movement. As that change in constraints is continuously placed upon the body, the system components reassemble until the movement becomes associated with those constraints. Once that occurs, spontaneous generation of the new pattern theoretically should be possible under those constraints[34].

Central Pattern Generator

Along with needing to know about motor control theories, it is important to understand a little about how rhythmic movements are produced when retraining gait. Early studies on rhythmic movement during locomotion suggested two hypotheses for the generation of rhythmic and alternating movements: 1) reflex chain model and 2) half-center model[35,36]. The reflex chain model, attributed to Charles Sherrington, proposes that feedback from sensory neurons excites interneurons that cause sequential reflex actions to occur on some spinal centers leading to activation of motor neurons to the antagonist muscle. Another scientist who worked with Charles Sherrington for a period of time, Thomas Graham Brown, instead believed that a central spinal network generated these rhythmic patterns in the motor neurons to antagonist muscles during locomotion. This concept is identified as the half-center model, now generally referred to as the central pattern generator (CPG). The main difference to focus on between these two models is the role of sensory feedback. In the reflex chain model, sensory feedback is needed to switch between different parts of a locomotor cycle. On the other hand, while rhythmicity in the CPG model can be influenced strongly by sensory feedback, it does not require sensory feedback in order to generate that fundamental rhythmic movement. Since this proposal by Brown, more and more evidence has been gathered supporting the CPG model, including but not limited to studies in cats, locusts, and salamanders[36]. The models for generation of rhythmic movement have become progressively more complex but continue to include the CPG component discovered by Brown. As more evidence is gathered, these models will continue to become more complex because no conceptual model is currently capable of explaining the wide variety of locomotor patterns that are generated.

Focus of the Study

This study is focused on altering a runner’s foot strike pattern. Previous studies have altered a runner’s foot strike pattern using methods that involved feedback including verbal, visual, and auditory. These methods, while sometimes successful, have been inconsistent with regard to the type and presentation of feedback. To reduce this inconsistency, a form of training not previously used to retrain running was selected. It is referred to as structured kinesthetic motor learning. Structured kinesthetic motor learning is learning through consistent repetitive movements. Essentially learning occurs through forcing subjects to perform a specified motor pattern repetitively without any deviation. Structured kinesthetic motor learning has previously been used to retrain stroke patients who had lost the ability to walk with a normal gait pattern using an elliptical that mimicked normal walking[37]. Based on the success of structured kinesthetic motor learning[38], it was decided to test if it could be used to teach runners a new foot strike pattern specifically focusing on a MFS pattern. Just as Bradford did, a modified elliptical gait trainer was used. A non-modified elliptical trainer produces a toe-down gait pattern. Figure 1-2 illustrates the elliptical trainer before it was modified. To create a motion similar to a MFS pattern, both stationary footplates were replaced with articulating footplates that could be positionally controlled electromechanically.

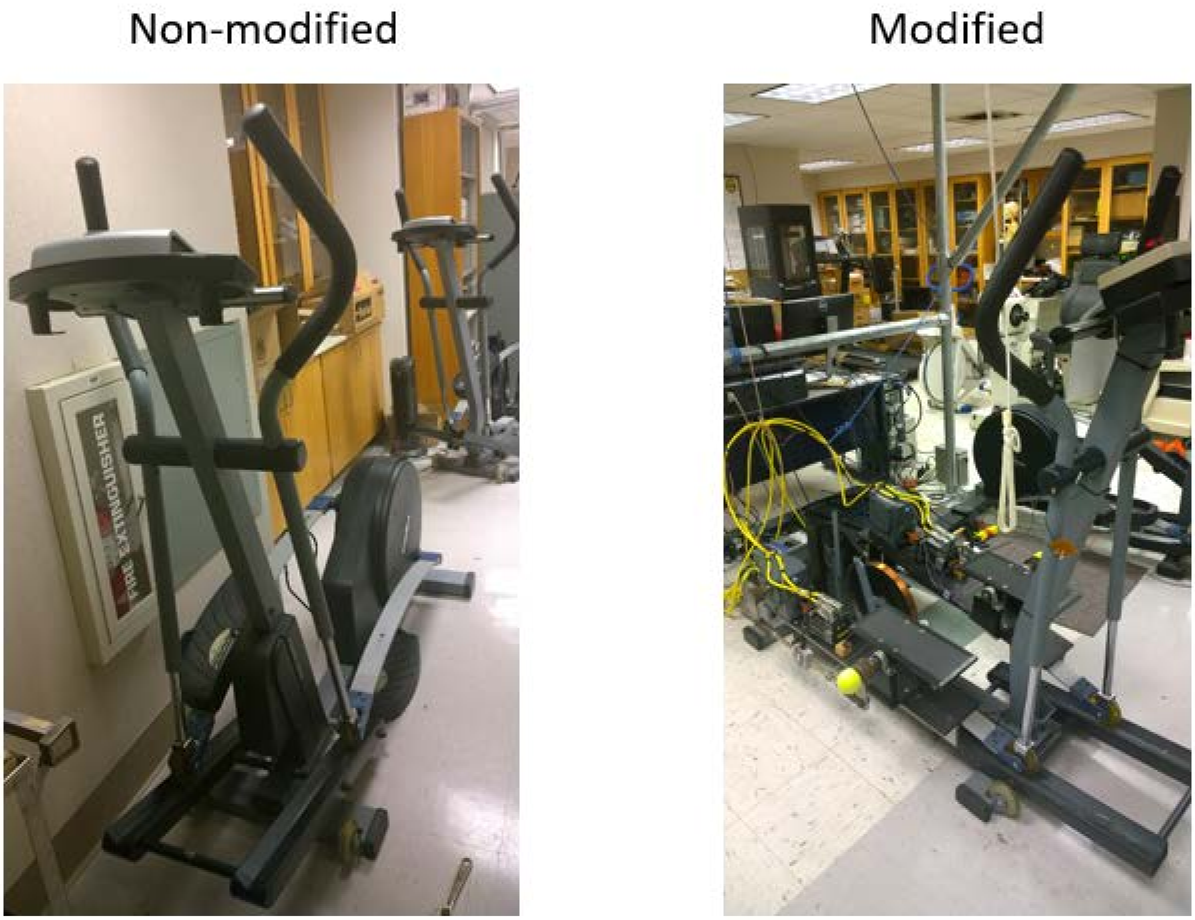
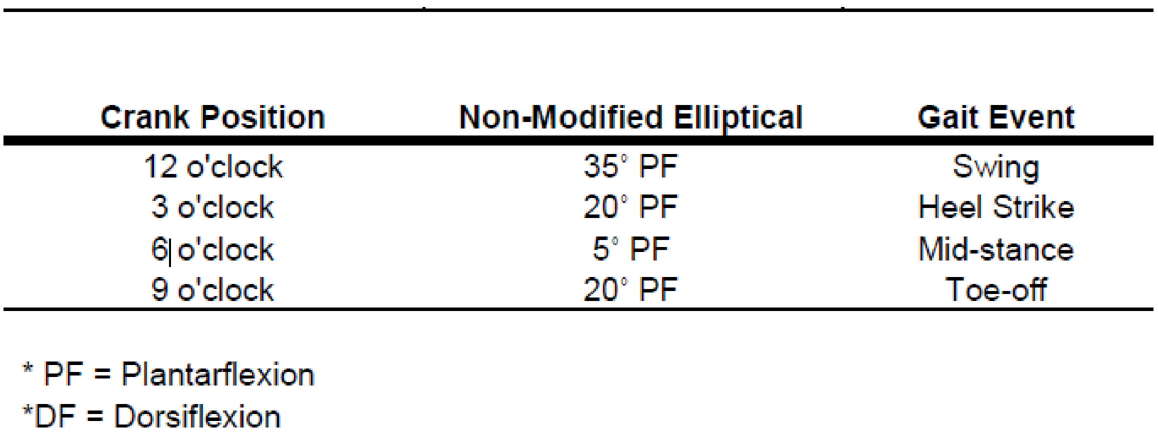


Figure 1-2: NordicTrack® CXT 910 elliptical trainer before modification (left) and after modification (right).

Table 1-1 contains footplate angles from the non-modified elliptical trainer, which was gathered previously in a study by Bradford. The angles were measured manually using a universal protractor. It was most evident that the elliptical trainer needed modification based on the footplate angle at heel strike. The non-modified elliptical trainer has the footplate plantar flexed at 20˚ when the footplate should instead be flat to allow for the heel and toe of the foot to strike the ground simultaneously.

Table 1-1: Non-modified elliptical trainer footplate angle measurements (with universal protractor) at positions representative of the different phases of gait. (Table credited to Bradford[37])



Crank Position	Non-Modified Elliptical	Gait Event
12 o'clock	35° PF	Swing
3 o'clock	20° PF	Heel Strike
6| o'clock	5° PF	Mid-stance
9 o'clock	20° PF	Toe-off

* PF = Plantarflexion
*DF = Dorsiflexion

By controlling the angle of the footplate, and ultimately the angle of the ankle, it is expected that the angles at the knee and hip during elliptical training will be similar to that of MFS.

Advantages

There are many advantages to using a gait trainer for this application. Elliptical trainers are user-driven systems that provide low-impact exercise and require subjects to stay engaged in the activity. This engagement has been shown to increase motor learning in subjects who are training with robot assistive devices. Training on an elliptical also allows the subject to learn the structured gait motion before attempting to run on their own. This reduces the possibility of the subject learning a gait motion that could increase the likelihood of injury.

Another advantage of using this type of gait trainer is the minimal cost. Elliptical trainers are found in most clinics and this reversible modification can be applied to the existing elliptical trainer for a minimal cost. Lastly and probably the most important advantage is the versatility of applications that this device could be used for. While the main focus of this research is on modification of gait motion in a running context, this device could easily be used for other gait training applications, making it advantageous in clinics as compared to other training devices.

Previous Work

A modified elliptical trainer designed for the use of training gait motion has been created in this lab previously with contributions by Mr. David Reese[39] and Dr. Courtney Bradford[37]. They both completed a successful design of a modified elliptical trainer with the focus of using it to help stroke patients relearn a natural RFS gait motion. This research study first started by redesigning the elliptical trainer to be lighter and more commercializable. Unfortunately, unforeseen obstacles did not allowed for the completion of this new iteration resulting in the final iteration used by Bradford to be used for this study.

Specific Aims and Hypotheses

The specific aims of this study were:

1. Characterize the ability to use structured kinesthetic motor learning to teach natural RFS runners to run with a MFS pattern using a modified elliptical trainer.
2. Determine the effect of modified elliptical training on the impact loads, knee moments, and stride frequency during running

The hypotheses of this study are:

1. Modified elliptical training will alter foot strike pattern when instructed to run with a MFS.
2. Modified elliptical training will decrease the impact loads, decrease knee moments, and increase stride frequency.

This study used an elliptical trainer that was modified to include an articulating footplate to mimic MFS foot motion during gait. The modification was applied to both footplates so that they rotated in the sagittal plane around the talocrural joint of the ankle. The talocrural joint was chosen because it is primarily responsible for plantarflexion and dorsiflexion of the foot. The integrity of the elliptical trainer was maintained. Modifications were engineered as “bolt-on” using a push-pull rod mechanism along with a servo motor and gearbox to control the position of the footplate via a camming profile.

Chapter 2: Material and Methods

Experimental Design

Subjects in the study were placed into two separate groups: 1) Control group 2) Intervention group. Kinetic and kinematic data were collected for eighteen healthy adult subjects (6 control, 12 intervention). Each subject was a natural RFS runner that had not experienced a severe injury in the last 12 months. The average age of the subjects was 29.7 years (SD=9.5), height of 1.69 m (SD=0.1), and mass of 69.3 kg (SD=11.1). A written informed consent was given by each of the subjects prior to beginning the experiment. This study was approved by the Virginia Commonwealth University Institutional Review Board (See Appendix A). Anthropometric data for subjects in each group are presented below in Table 2-1 and Table 2-2.

Table 2-1: Anthropometric data of the subjects in the control group who participated in the study.

Subject	Type	Gender	Age	Height (m)	Mass (kg)
1	Control	M	28	1.9	84.4
2	Control	F	32	1.6	77.9
3	Control	F	29	1.5	54.9
4	Control	M	24	1.8	69.6

5	Control	F	20	1.6	59.4
6	Control	M	28	1.7	71.7
Mean			26.8	1.7	69.6
SD			4.2	0.1	11.1

Table 2-2: Anthropometric data of the subjects in the intervention group who participated in the study.

Subject	**Type**	**Gender**	**Age**	**Height (m)**	**Mass (kg)**
1	Intervention	M	26	1.8	83.5
2	Intervention	F	23	1.6	49.7
3	Intervention	M	22	1.8	73.3
4	Intervention	F	24	1.6	57.1
5	Intervention	F	42	1.7	59.8
6	Intervention	M	34	1.8	83.3
7	Intervention	M	27	1.8	74.9
8	Intervention	F	24	1.7	72.1
9	Intervention	F	34	1.6	76.1
10	Intervention	F	36	1.6	55.7
11	Intervention	F	21	1.5	63.8
12	Intervention	M	60	1.9	80.8

Mean			31.1	1.7	69.2
SD			11.2	0.1	11.6

The elliptical trainer model used in this research study was a NordicTrack CXT 910. Control subjects trained on a non-modified version of the elliptical while intervention subjects trained on a modified version of the elliptical with the articulating footplates. The resistance function of the elliptical was set to zero to mimic normal level surface gait. Prior to training, each subject had a baseline gait analysis completed on an instrumented treadmill while measuring lower body kinetics and kinematics. Motion data were captured at 120 Hz with an eight camera, Vicon motion analysis system (Vicon, Oxford). Force data were collected using two synchronized force plates (AMTI, Watertown, MA) at a sampling rate of 1200 Hz. Subjects were asked to run at a self-selected speed wearing standardized footwear. Two running conditions were imposed; the first was to run using their natural/normal technique. The second was to run in a MFS pattern after being provided verbal instruction. After baseline gait analysis, subjects completed eight elliptical training sessions within a two-week span. All subjects trained on their respective elliptical trainers for 20 minutes during the first session and increased to 30 minutes of training by the third training session. Intervention subjects trained on their elliptical with the modified elliptical foot pedals alternating between a RFS and a MFS pattern camming profile. The ratio of time the foot pedals mimicking a RFS to mimicking a MFS was equal until it gradually decreased from training session four to training session eight. This progression is illustrated in Figure 2-1.

Figure 2-1: Amount of time during each training session that the intervention group subject was training with a rearfoot strike (RFS) and a midfoot strike (MFS).

After completion of the eight training sessions, another gait analysis was completed with the same parameters and protocol that had been used in the baseline gait analysis.

Gait Analysis Protocol

Subjects were asked to wear gym attire to the gait analysis session. Standardized footwear was provided to each subject to reduce performance variance. If necessary, clothing was tied back to expose body landmarks where the reflective markers would be placed. Reflective spherical markers were placed at defined positions on the subject's lower extremities using double sided tape. These positions included the subject's trunk and lower extremities at the iliac crests, greater trochanters, medial and lateral femoral condyles, medial and lateral malleoli, posterior and lateral heels, and 1st and 5th metatarsal heads. Rigid arrays of markers (cluster markers) were also placed on thighs and lower legs to collect triplanar rotation and translation data. Anatomical/joint markers (those defining joint centers and segment coordinate axes) were left on only during the static calibration trial[40]. Locations of reflective markers were palpated using standard techniques.

Once the reflective markers had been attached, the subject was asked to stand on the treadmill in a staggered leg position with their arms crossed over their chest. The static trial was measured using an eight camera, Vicon motion analysis system (Vicon, Oxford). The anatomical/joint markers were then removed. Each subject then ran at a self-selected speed with their natural running technique. Once they felt comfortable, kinetic and kinematic data was collected for 30 seconds. The subject was then instructed to run to the best of their ability with what they believed was a MFS technique. Again, once they felt comfortable enough kinetic and kinematic data was collected for 30 seconds. Following completion of these trials, the treadmill was slowed and the reflective markers were removed.

Elliptical Training

Subjects were asked to wear comfortable clothing and athletic shoes to each of the elliptical training sessions. Prior to training it was explained how to run on the elliptical and how to press the emergency stop button if anything odd were to occur during the session. Subjects then ran on the elliptical for the allotted amount of time associated with that training session. Control subjects trained on the elliptical at a self-selected pace while the intervention subjects trained on the modified elliptical at 1 mph due to mechanical limitations of the device.

Control subjects ran with the same gait pattern associated with the NordicTrack CXT 910 for the entire training session. Intervention subjects alternated between running with a RFS technique and a MFS technique through manipulation of the foot pedals on the modified elliptical trainer. The RFS technique progressively decreased after the third session with it occurring one third at the beginning of each session, one third in the middle, and one third towards the end. By the last session, runners were training solely with a MFS technique.

Data Processing

The data collected was processed using Visual 3D (Visual 3D Germantown, Maryland) as well as the computing software Matlab. The joint kinematics for each stance phase during the gait analysis were calculated using an X-Y-Z Cardan angle rotation sequence. The variable of interest to determine foot strike was foot angle at initial contact (FIC). While that was the focus of this research study, ground reaction forces, knee moments, and stride frequency were measured concurrently during gait analysis. The ground reaction force variables measured were vertical impact peak (VIP), vertical average loading rate (VALR), and vertical instantaneous loading rate (VILR). These were important to measure since impact loading variables have been linked to other running-related injuries including tibial stress fractures, plantar fasciitis and knee osteoarthritis[27]. Similar to other studies, loading rates were calculated between 20% and 80% on the linear portion between foot initial contact and VIP (illustrated in Figure 2-2). This portion of the curve was chosen for this calculation because it is the most linear portion of the initial loading phase. VALR was calculated as the change in total force over that time period, and VILR was calculated as the peak sample-to-sample loading rate over that time period[41]. When a distinct VIP did not occur, during the midfoot strike pattern running trials, the VIP was determined to be where there was a shift in the vertical ground reaction force slope[42]. The majority of the time this was found to occur closer to initial contact than when there was a distinct VIP. Body weight was used to normalize the loading rates.

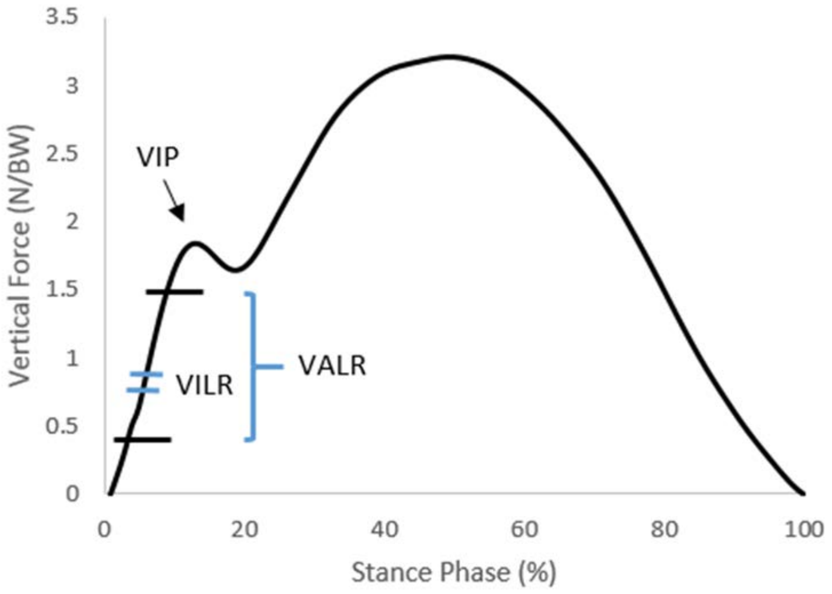


Figure 2-2: Typical vertical ground reaction force curve of a runner during the stance phase highlighting VIP, VALR, and VILR.

The knee moments measured were peak knee flexion moment (KFM), peak knee adduction moment (KAM), and peak knee internal rotation moment (KIRM). These variables have been seen to be related to injuries as well as be affected by type of foot strike[43]. The data was processed through Visual 3D software.

The kinematic data was low-pass filtered using an eighth-order-zero phase lag Butterworth filter with a cutoff frequency of 12Hz. All kinematic data was processed in Visual 3D (Visual 3D Germantown, Maryland). The kinetic data was low-pass filtered using a fourth-order, phase-corrected Butterworth filter with a cutoff frequency of 50Hz. To determine foot strike and toe off, a threshold of 10 N in the vertical ground reaction force was used[26]. Matlab was used to calculate kinetic data variables. Source code can be found in Appendix B.

Stride frequency (SF) was measured because studies have shown it to be affected by foot strike[7,44,45]. This was calculated by using step time, the duration of time between foot-falls. Step time was used to calculate stride length using the following equation where sT is length of time between steps, and v is treadmill velocity[46].

$$SF = \frac{1}{2 * sT}$$

To better compare SF between subjects, SF was linearly normalized by treadmill velocity and leg length of each subject.

A between and within measures statistical analysis was used to compare variables of interest at natural RFS running and MFS running between pre-training and post-training gait analysis data. To determine the effects of the modified elliptical, the data were separated into two groups: (1) subjects training on the non-modified elliptical (control subjects) and (2) subjects training on the modified elliptical (intervention subjects). These became the between measures for the analysis. The within measures were foot strike, RFS or MFS, and time, pre-training and post-training. The use of post-hoc, two-tailed, and pairwise comparisons ($\alpha = 0.05$) determined significant differences between each parameter. All statistical testing were performed using SPSS (SPSS, Chicago, Illinois).

Modifications to the Elliptical Trainer

As stated earlier, the modified elliptical used in this research study was created from contributions by Mr. David Reese[39] and Dr. Courtney Bradford[37]. An elliptical trainer was selected because it produced a gait like movement and reduced lower extremity impact during training (illustrated in figure 2-3).

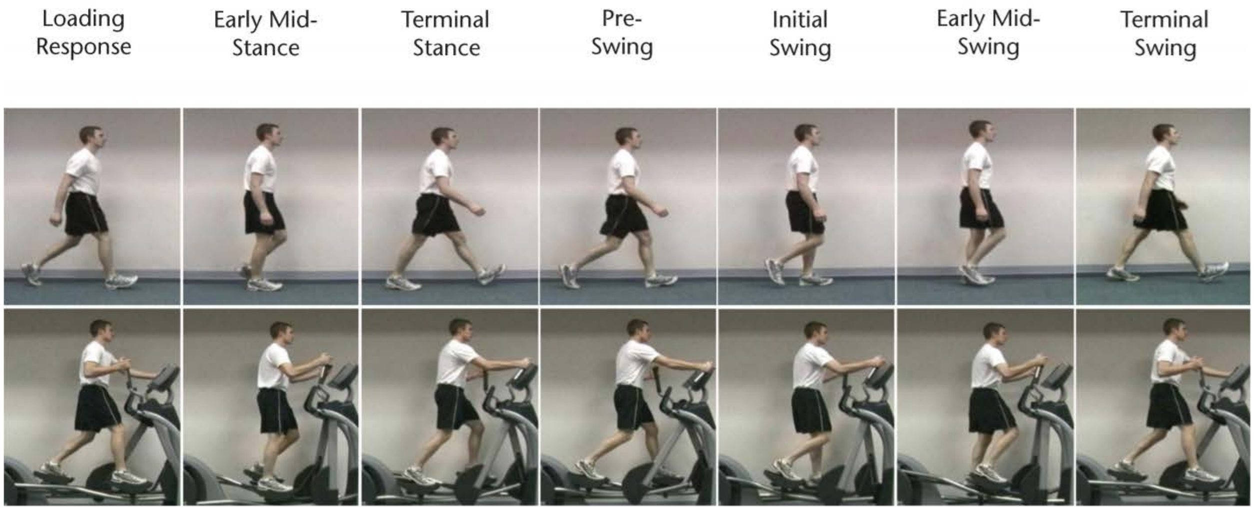


Figure 2-3: Using a similar elliptical, Burnfield et al. was able to show that the gait cycle could be mimicked on an elliptical trainer. (Picture credited to Burnfield[38])

In a previous kinematic analysis study done by Bradford, the NordicTrack CXT 910 was shown to have similar hip and knee motions to that of level surface walking, but different ankle joint angles in the sagittal plane[37]. With that in mind, the elliptical needed to be modified to better represent level surface walking. The following components needed to be included in our modifications:

1. Greater footplate range-of-motion (ROM)
2. Capacity for average to above average weighing subjects
3. Maximum rotational speed of the footplate needs to match normal level surface walking

In order to simulate ankle joint angles of surface level walking, the footplates were redesigned. It was determined that the footplates needed to have a ROM at a minimum of 30 degrees of plantarflexion and dorsiflexion. To accommodate for this, the footplate was elevated above the elliptical ski to allow for the required footplate articulation. The original ski on the elliptical is a leaf spring ski meaning, designed to provide shock absorption; however, we desired a stiffer, more rigid ski to accommodate the footplate design. Consequently, an aluminum plate with the footplate components, which were also mainly made of aluminum, was bolted directly on top of the existing leaf spring ski. Aluminum was used because it is strong and light, minimizing the addition of mass to the system. To control the articulation of the footplate, a push-pull rod mechanism was used to transfer motion from a gearbox to the footplate. This design allowed for the greatest ROM, placement of the drive components on the ski, and no interference with the footplate articulation. The drive components used were a servo motor and a gearbox. The gearbox used was a 60:1 ratio zero-backlash worm gearbox, selected for its high gear ratio and self-locking abilities. Because of the limited amount of space on the ski and minimizing the added mass to the system, a high gear ratio was chosen to reduce the size of the motor needed to drive the footplate motion.

Each footplate is controlled by a separate single-axis controller and were mounted at the rear of the elliptical. Each controller sends the coded CAM profile to the associated motor drive to amplify the signal. The signal is then sent to the motor to change the position of the footplate. Each controller monitors feedback from the motor to confirm it moved to the correct position and adjusts as needed. The left footplate movement was designed to be 180° out of phase with the right footplate. These controllers also receive feedback from a common optical encoder that tracks the position of the flywheel to synchronize the footplate movement pattern to normal events in the gait cycle (i.e. heel strike and toe off). The block diagram below illustrates this.

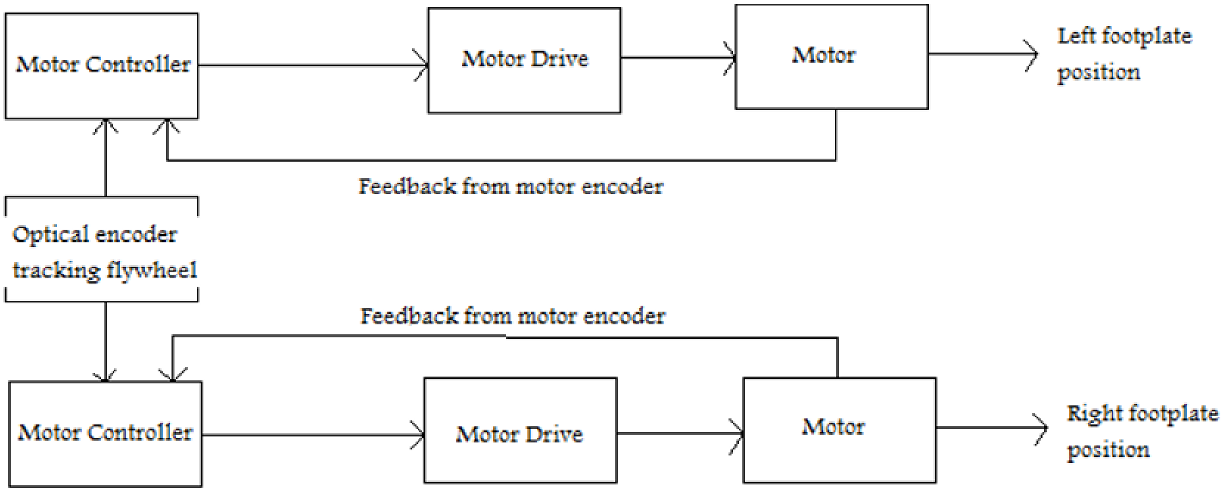


Figure 2-4: Block diagram of how the footplates are controlled by the optical encoder. (Picture credited to Bradford[37])

The motoric force to drive the elliptical motion is provided solely by the user. When force is applied, the flywheel and thus the encoder begin to turn. The encoder feedback is used to determine footplate position. The position of the footplates relative to the flywheel are designed to mimic level surface walking. For example, a heel strike occurs when the ski is in the most forward position and toe off occurs when the ski is in the most rearward position. For controller programming, see Appendix C.

A few safety precautions were included in the design to decrease the possibility of injury. One of these was an emergency stop button placed on the console of the elliptical trainer (Figure 2-5). If anything were to go wrong and it was necessary to stop the motion of the footplates, the subject or operator could use the emergency stop button to stop the articulation of the footplates. The footplate ROM was also limited by end of travel limit switches, which were wired using a negative digital logic circuit. As a result, if the footplates travel too far or a wire breaks, the safety protocol would be engaged and the footplates would stop. There are also torque and error limits applied to the motor powering the footplates via the controlling software, providing an additional level of safety.

Figure 2-5: Red emergency button on the right side of the elliptical that the subject can press in case there is a need to stop the rotation of the footplates.

Our two other desired components of the modified device were also achieved. The capacity for the device is 250lbs, which we believe is sufficient to accommodate the majority of the population. Also, the device had a greater rotational speed than that needed to match average walking cadence (1 step/second = 1 full rotation every 2 seconds).

Camming Profiles

Since two different running techniques were imposed, RFS and MFS, it was necessary to create two different camming profiles for the controller to use when driving footplate positions. The RFS camming profile was previously created and mimics a normal heel strike gait pattern. The MFS camming profile was created to have a similar toe off phase, but instead of landing on the heel at the ski's most forward position, the subject would land with their foot flat (with a foot angle of 0° relative to horizontal). Table 2-3 illustrates footplate angles at discrete flywheel positions and the associated gait phases.

Table 2-3: Comparison between RFS and MFS and their footplate angles with respect to the horizontal. Flywheel position refers to positions on a clock while looking at the right side of the trainer.

Flywheel Position (Right Pedal)	RFS	MFS	Gait phase
3	20° DF	0°	Heel strike
6	0°	0°	Mid-stance
9	15° PF	15° PF	Toe-off
12	32° PF	32° PF	Swing

Figure 2-6 temporally illustrates foot angle with respect to the horizontal for both camming profiles compared to normal walking for one complete gait cycle (from foot contact to re-contact of the same foot). Focusing on just the two camming profiles, the only difference between them is during the heel strike phase (0-20% and 80%-100% of the gait cycle). The RFS camming profile has a foot angle of 20° dorsiflexion at heel contact and the MFS camming profile having 0° dorsiflexion at the same position. Comparing the camming profiles to the foot angle seen in normal gait, the greatest difference occurs during toe-off (60%-80% gait cycle) where much greater plantarflexion is observed in normal gait compared to what the camming profiles can provide. This difference was a result of mechanical limitations of the system. It was observed that while subjects were training on the modified elliptical many would lift their heel off of the pedal during this phase providing more normal plantarflexion even though they were instructed not to. This was not considered to be a limitation in the design, but instead a natural accommodation to the pattern.

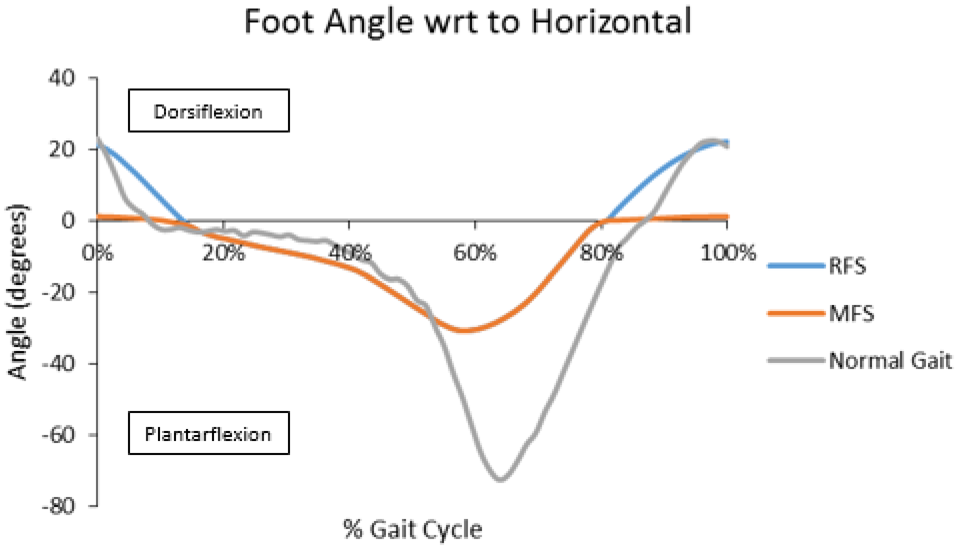


Figure 2-6: Representation of foot angle during the gait cycle comparing the RFS and MFS camming profiles and normal gait. Dorsiflexion is positive and plantarflexion is negative. (Normal gait data credited to Bradford[37])

Figure 2-7 illustrates the new device being used with each of the camming profiles. As explained previously, the footplates change position based on the position of the flywheel. Starting with the images on the left and the heel strike phase, the greatest difference between the two camming profiles is seen. In the RFS camming profile the footplate is tipped backward with the toe up in the air. This is to represent an initial contact with the heel. Conversely, in the midfoot camming profile the footplate is flat to represent an initial contact with the midfoot rather than the heel. In the next image at mid-stance the flywheel reaches clock position 6 where the camming profiles are similar in that both footplates are parallel to the floor. Clock position 9 is in correspondence to toe off in the gait cycle and both camming profiles have the footplate tipped downward to simulate the foot leaving the ground to enter the swing phase. Lastly at mid-swing, when the flywheel is at clock position 12, the footplate for both camming profiles are again the same since the only difference between the camming profiles occurs at heel strike.

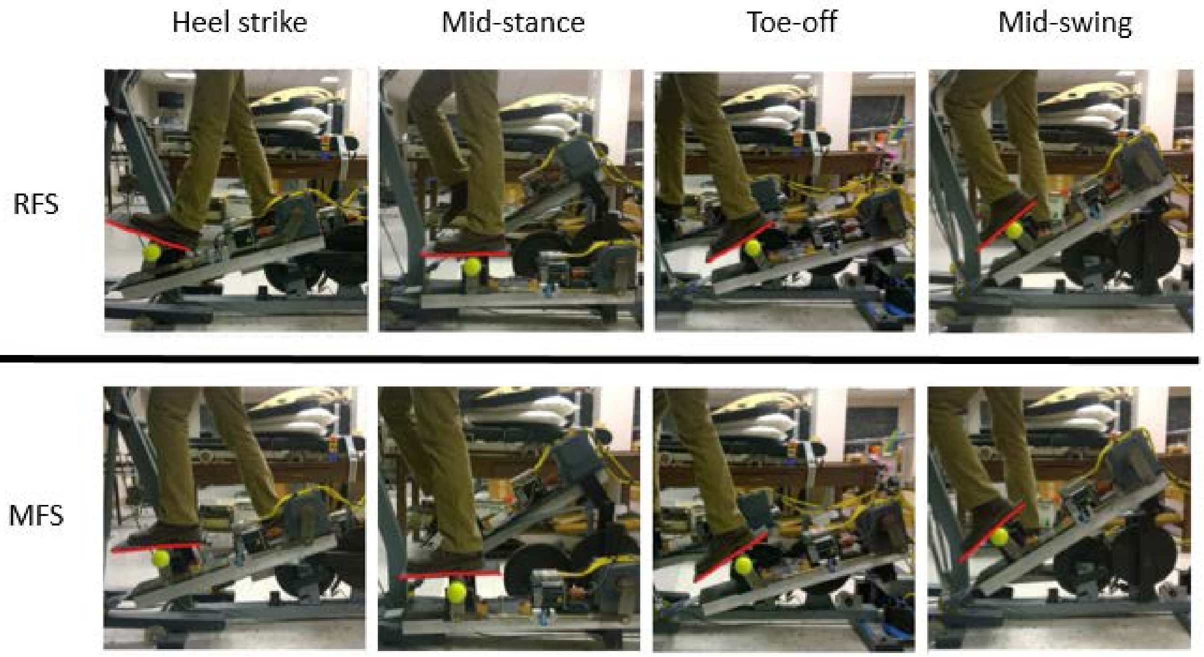


Figure 2-7: Elliptical camming profiles. The RFS camming profile on the top row and the MFS camming profile on the bottom row. The photos represent four different phases in the gait cycle.

Structured Kinesthetic Motor Learning

The use of technology in motor learning applications is on the rise as a result of the patients attending therapy more frequently, sometimes with limited therapist assistance[47]. While technology, specifically robotics, has been helpful in the rehabilitation of impairments, in some cases the robots are moving the patient’s limbs for them. While this may be beneficial for a patient that is paralyzed, it is not the best mechanism for motor learning[48]. One example of a robotic exoskeleton is the Lokomat. The Lokomat is designed to help patients regain a desired gait pattern by assisting the movement of their lower body in this desired gait pattern. In regards to motor learning, this device is not optimal because the robot moves the patient's legs without requiring any work from the patient. As a result, the patient can fall asleep while in these robotic legs[48].

One benefit to having runners train on an elliptical is that it is entirely powered by the user. This way the user is require to be engaged in the activity while training. Repetition during motor learning has also been discovered to be important during motor learning, but some variability in exercises during training has been shown to keep subjects engaged, improve learning effects, and improve learning retention[47,49]. Based on this evidence, this study implemented switching between the CAM Profiles during the training sessions. Since the subjects were RFS runners, the RFS CAM profile was chosen to be something that was familiar and felt more comfortable as they transitioned to a MFS. The time of presentation of the RFS CAM profile was decreased while the MFS CAM profile was increased as the subject completed more training sessions to first aid in transition and second to increase the repetition of the desired MFS running.

Another term that needs to be defined is structured kinesthetic motor training. Structured kinesthetic motor training is defined as forcing subjects to train in a specified motor pattern. The modified elliptical trainer implemented this concept by forcing subjects to train with the specified CAM profile. Modifications were not made to either CAM profile during each of the training sessions resulting in the subjects repeating the same motor action without variability.

Chapter 3: Results

Data analyses were performed on four groups: pre-training control group gait analysis (C-PRE), post-training control group gait analysis (C-POST), pre-training intervention group gait analysis (I-PRE), and post-training intervention group gait analysis (I-POST). For each of the measured variables, the pre and post training RFS trials were compared and separately the pre and post training MFS trials were compared. It should be noted that in all figures the asterisk represents a significant difference ($p = <0.05$) and that all data were collected on an instrumented treadmill that included both kinetic and kinematic elements.

Foot Strike Transition

Alterations of foot strike pattern by subjects after training on their respective elliptical trainers were determined by their foot angle at initial contact (FIC). As expected, in all groups FIC was lower when subjects were instructed to run with a MFS as compared to running naturally in their RFS pattern. Table 3-1 and Figure 3-1 illustrate FIC for RFS running and MFS running for each of the groups.

Table 3-1: FIC descriptive statistics comparing group, foot strike, and time.

	Mean	Standard Deviation	Minimum	Maximum	Range

Control	RFS	PRE	17.65	7.00	7.92	34.61	26.68
		POST	16.40	6.57	5.27	31.71	26.44
	MFS	PRE	9.47	10.54	-5.88	31.29	37.18
		POST	9.57	7.89	-3.99	25.65	29.64
Intervention	RFS	PRE	16.34	3.86	7.76	24.99	17.23
		POST	15.89	3.99	6.72	26.79	20.07
	MFS	PRE	5.54	6.86	-5.92	23.84	29.76
		POST	4.30	6.92	-5.67	20.77	26.45

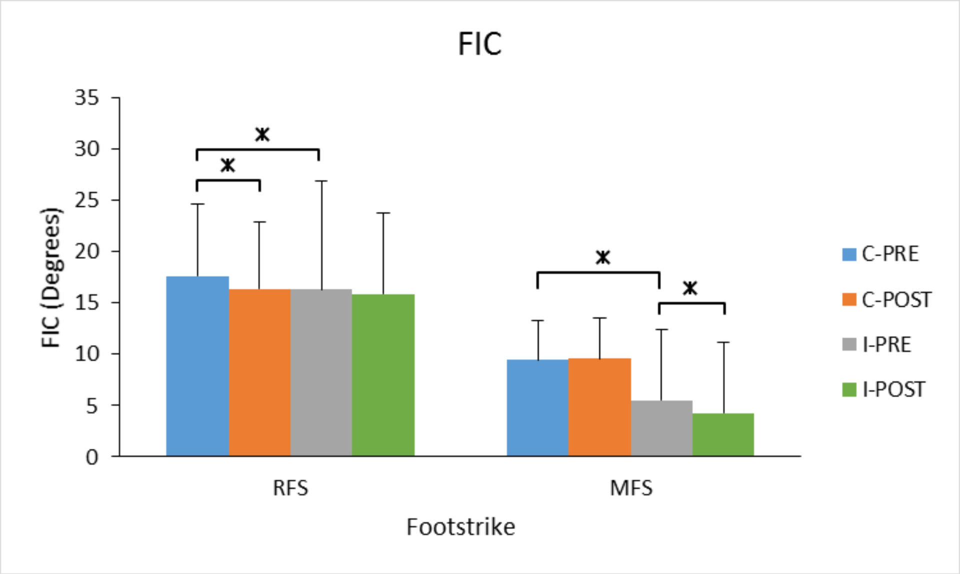


Figure 3-1: FIC with respect to the horizontal for each foot strike and each group. An asterisk represents a significant difference between groups (p = <0.05).

The RFS trials showed a significant decrease in the C-PRE group when compared to the C-POST group, but when comparing the I-PRE and I-POST group there was no change in FIC. In the MFS trials there was no change in FIC after training on the non-modified elliptical (C-PRE to C-POST); however, comparing FIC in the I-PRE and I-POST group there was a significant decrease in the I-

POST group. There was also a significant difference between the C-PRE and I-PRE groups in both the RFS and MFS trials.

Impact Forces

Vertical loading during the stance phase of running has been a major focus when looking at foot strike alteration because of its role in running injuries. The ground reaction force variables vertical impact peak (VIP), vertical average loading rate (VALR), and vertical instantaneous loading rate (VILR) for each of the groups were measured and are represented in the following tables and plots below.

Table 3-2: VIP descriptive statistics comparing group, foot strike, and time.

			Mean	Standard Deviation	Minimum	Maximum	Range
Control	RFS	PRE	1.88	0.72	0.90	3.39	2.49
		POST	1.54	0.36	0.98	2.87	1.89
	MFS	PRE	1.85	0.74	1.03	3.69	2.66
		POST	1.53	0.27	1.05	2.58	1.54
Intervention	RFS	PRE	1.37	0.21	0.75	1.86	1.12
		POST	1.35	0.21	0.86	1.94	1.08
	MFS	PRE	1.39	0.27	0.37	2.01	1.64
		POST	1.31	0.31	0.40	1.91	1.51

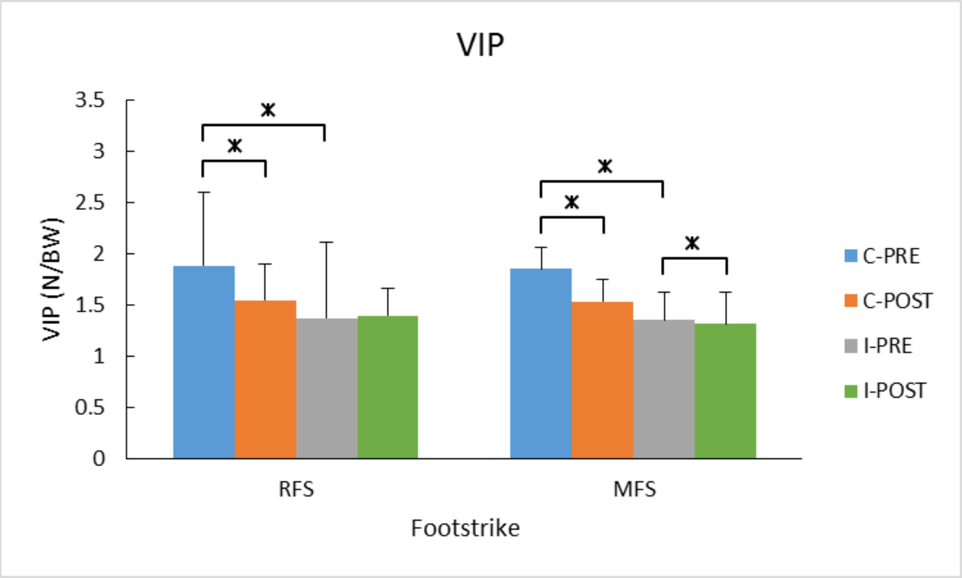


Figure 3-2: VIP for each foot strike in each group. VIP was normalized by body weight (BW). An asterisk represents a significant difference between groups (p = <0.05).

Table 3-3: VALR descriptive statistics comparing group, foot strike, and time.

			Mean	Standard Deviation	Minimum	Maximum	Range
Control	RFS	PRE	49.78	16.58	13.27	92.99	79.72
		POST	42.06	11.76	18.86	81.39	62.53
	MFS	PRE	38.76	14.16	8.15	78.30	70.15
		POST	38.16	11.79	15.92	75.44	59.52
Intervention	RFS	PRE	41.01	12.32	5.92	76.40	70.48
		POST	41.20	12.42	16.26	80.71	64.45
	MFS	PRE	34.20	11.99	14.04	76.15	62.11
		POST	34.26	12.28	13.09	87.06	73.97

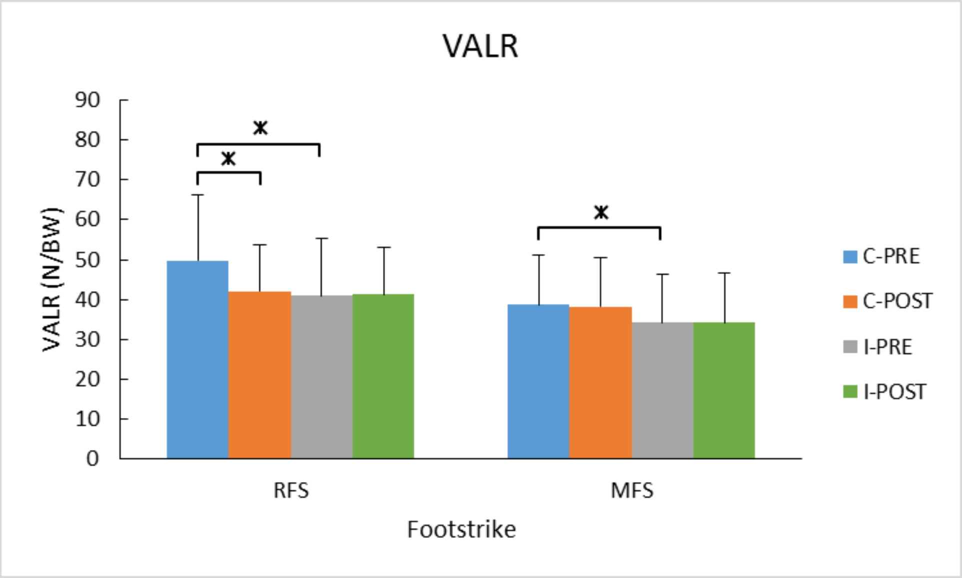


Figure 3-3: VALR for each foot strike in each group. VALR was normalized by body weight (BW). An asterisk represents a significant difference between groups (p = <0.05).

Table 3-4: VILR descriptive statistics comparing group, foot strike, and time.

			Mean	Standard Deviation	Minimum	Maximum	Range
Control	RFS	PRE	55.78	17.31	23.33	101.79	78.46
		POST	47.86	11.56	26.35	95.78	69.43
	MFS	PRE	48.49	14.17	20.60	85.65	65.05
		POST	44.35	11.31	18.79	79.74	60.95
Intervention	RFS	PRE	46.25	12.41	20.58	78.26	57.68
		POST	46.39	12.82	21.38	80.71	59.33
	MFS	PRE	40.16	13.97	17.33	94.73	77.40
		POST	40.34	13.58	13.35	87.06	73.71

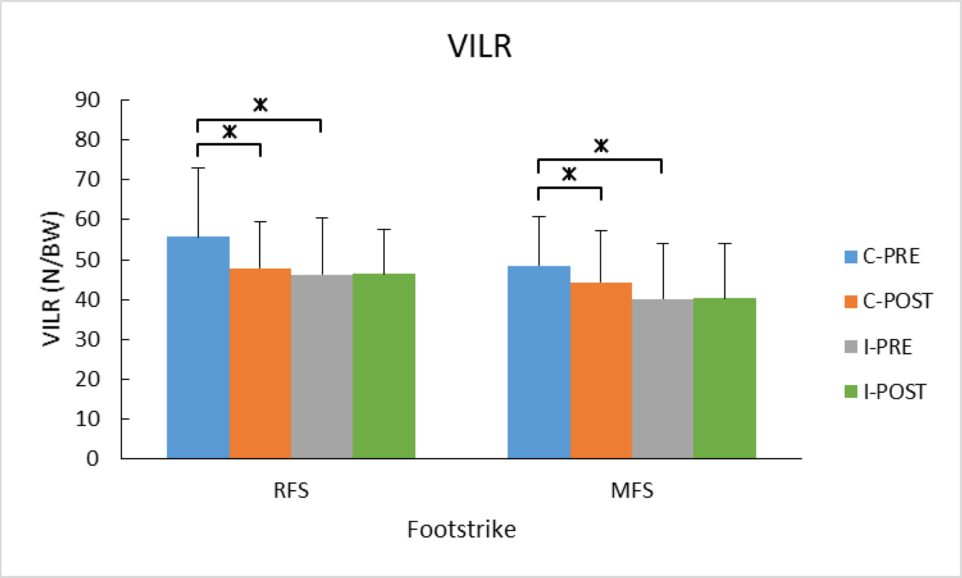


Figure 3-4: VILR for each foot strike in each group. VILR was normalized by body weight (BW). An asterisk represents a significant difference between groups (p = <0.05).

A significant difference was observed in each of the impact force variables in both the RFS and MFS trials between the C-PRE and I-PRE groups.

When comparing the VIP between RFS and MFS, results varied between groups. In both the C-PRE and I-PRE groups there was a significant increase in VIP when subjects were instructed to run with a MFS compared to when they ran with their natural RFS pattern. C-POST VIP did not change between RFS and MFS and I-POST VIP significantly decreased from RFS to MFS. Comparing just the RFS trials, VIP significantly decreased from C-PRE to C-POST no change occurred between I-PRE to I-POST. In the MFS trials there was a significant decrease in VIP after training on either elliptical trainer.

Similar changes observed in VIP were also seen in VALR. In the RFS trials there was a significant decrease from C-PRE to C-POST and no change in VALR from I-PRE to I-POST. In the MFS trials there was no change in VALR after training on either the non-modified elliptical or the modified elliptical.

VILR had similar results in both the RFS trials and the MFS trials. Comparing the groups just with the RFS trials and separately just the MFS trials, in both there was a significant decrease from C-PRE to C-POST and no change from I-PRE to I-POST.

Comparing the foot strike trials to each other, subjects ran with significantly higher VALR and VILR in all groups when running with a RFS compared to a MFS.

Peak Knee Moments

Peak knee moments during the stance phase in the sagittal (knee flexion moment), frontal (knee adduction moment), and transverse (knee internal rotation moment) planes were measured for each of the groups. Each of these are depicted in the tables and plots below.

Table 3-5: KFM descriptive statistics comparing group, foot strike, and time.

			Mean	Standard Deviation	Minimum	Maximum	Range
Control	RFS	PRE	1.18	1.02	-0.66	2.88	3.54
		POST	2.43	1.08	0.52	4.60	4.08
	MFS	PRE	1.17	0.95	-0.64	2.76	3.40
		POST	2.19	1.24	0.03	4.29	4.26
Intervention	NORM	PRE	1.85	0.32	1.18	2.48	1.30
		POST	1.91	0.40	1.12	3.13	2.01
	MFS	PRE	1.57	0.55	-0.03	2.76	2.78
		POST	1.63	0.57	0.14	2.58	2.43

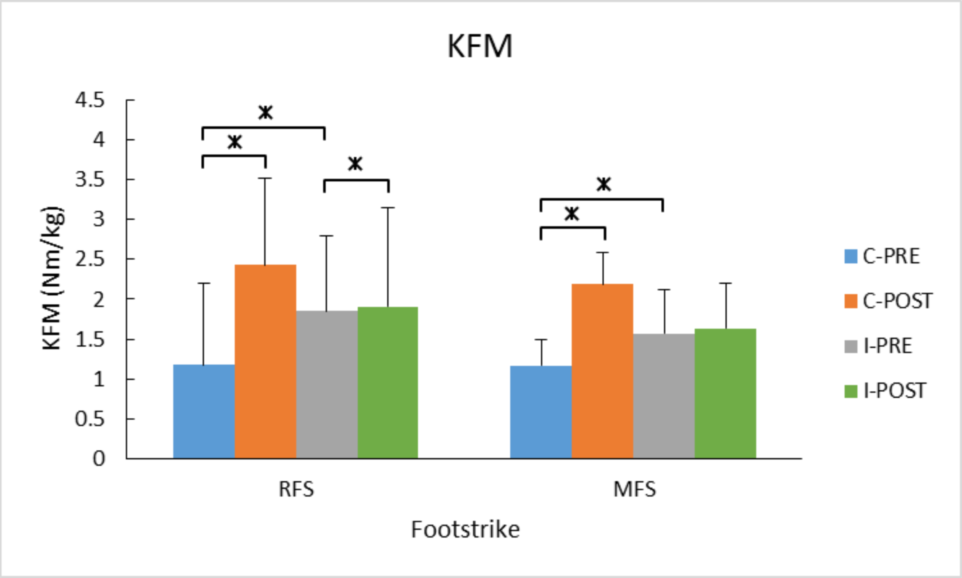


Figure 3-5: KFM for each foot strike in each group. An asterisk represents a significant difference between groups (p = <0.05).

Table 3-6: KAM descriptive statistics comparing group, foot strike, and time.

			Mean	Standard Deviation	Minimum	Maximum	Range
Control	RFS	PRE	1.64	1.24	.43	3.96	3.53
		POST	1.10	.95	.19	3.77	3.57
	MFS	PRE	1.43	1.07	.33	3.84	3.51
		POST	.71	.49	.02	1.51	1.49
Intervention	RFS	PRE	.79	.33	.24	1.59	1.35
		POST	.63	.22	.16	1.29	1.13
	MFS	PRE	.73	.38	.00	1.74	1.74
		POST	.58	.34	.01	1.58	1.57

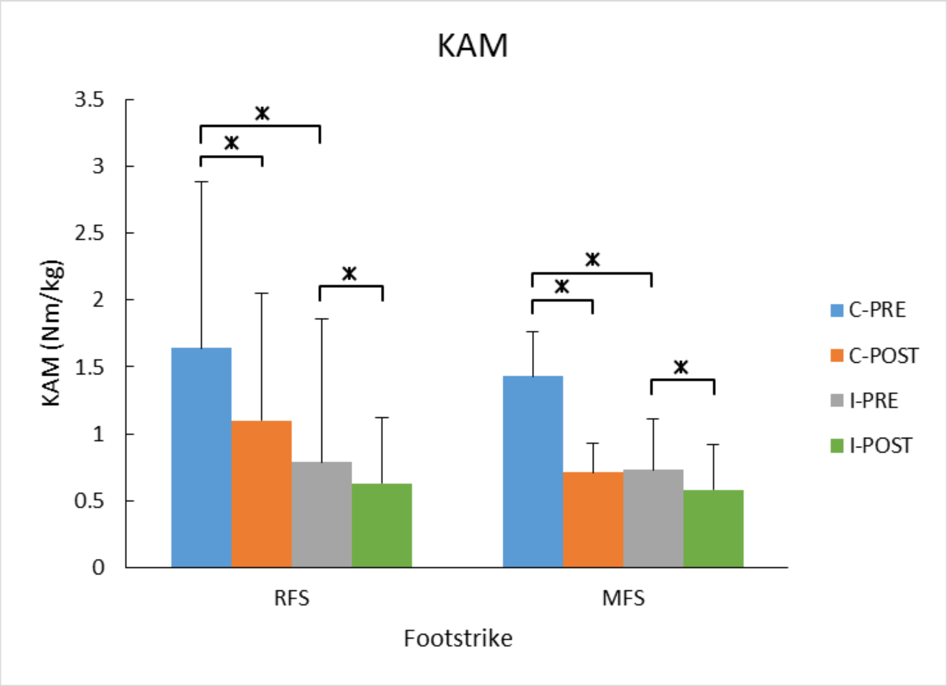


Figure 3-6: KAM for each foot strike in each group. An asterisk represents a significant difference between groups (p = <0.05).

Table 3-7: KIRM descriptive statistics comparing group, foot strike, and time.

			Mean	Standard Deviation	Minimum	Maximum	Range
Control	RFS	PRE	.90	.61	.31	2.19	1.88
		POST	.61	.38	.09	1.69	1.60
	MFS	PRE	.77	.43	.13	1.86	1.73
		POST	.40	.24	-.04	.83	.87
Intervention	RFS	PRE	.53	.13	.21	.86	.65
		POST	.51	.14	.12	.98	.86
	MFS	PRE	.48	.19	-.02	.90	.92
		POST	.47	.18	.03	.83	.80

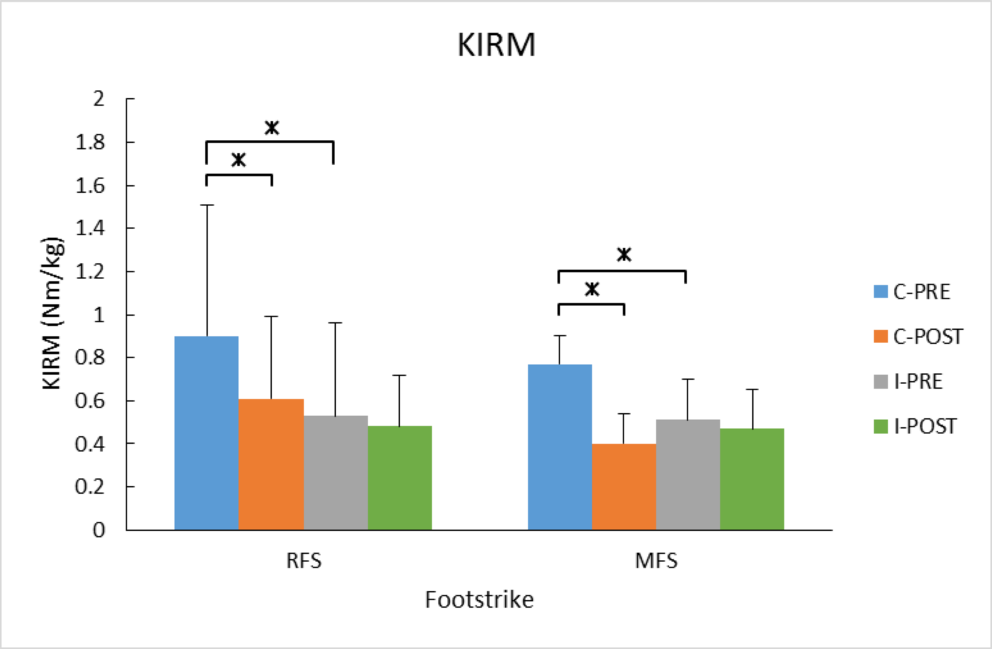


Figure 3-7: KIRM for each foot strike in each group. An asterisk represents a significant difference between groups (p = <0.05).

After elliptical training, there were differences in the peak knee moments. These differences were simply an increase or decrease in the peak knee moment and occurred in the same location before and after training on either elliptical. The following figures of the three knee moment graphs during stance phase are from a representative subject.

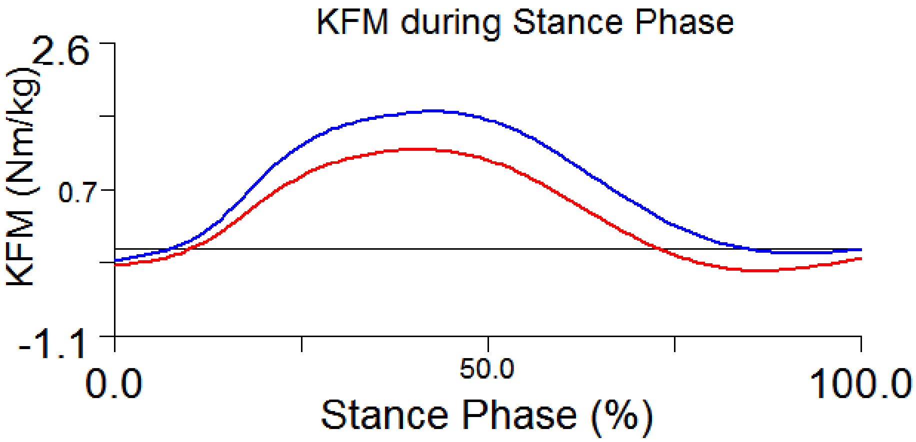


Figure 3-8: KFM from a representative subject showing KFM before (red) and after (blue) modified elliptical training.

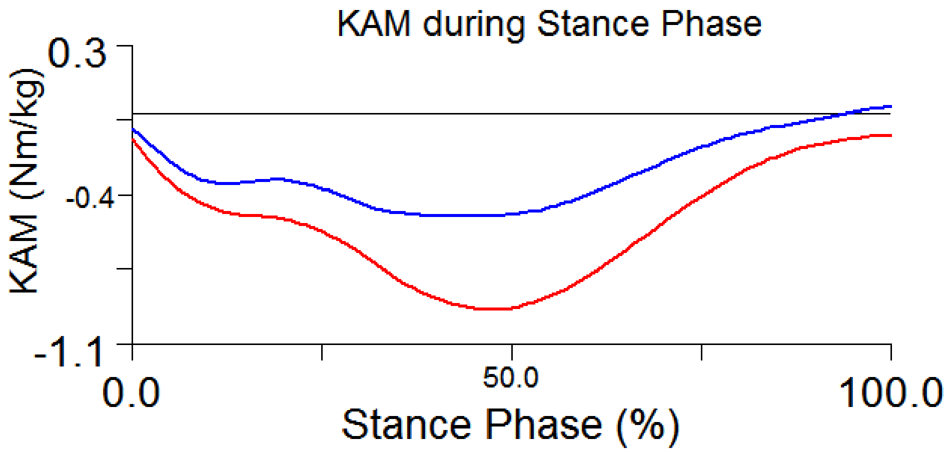


Figure 3-9: KAM from a representative subject showing KAM before (red) and after (blue) modified elliptical training.

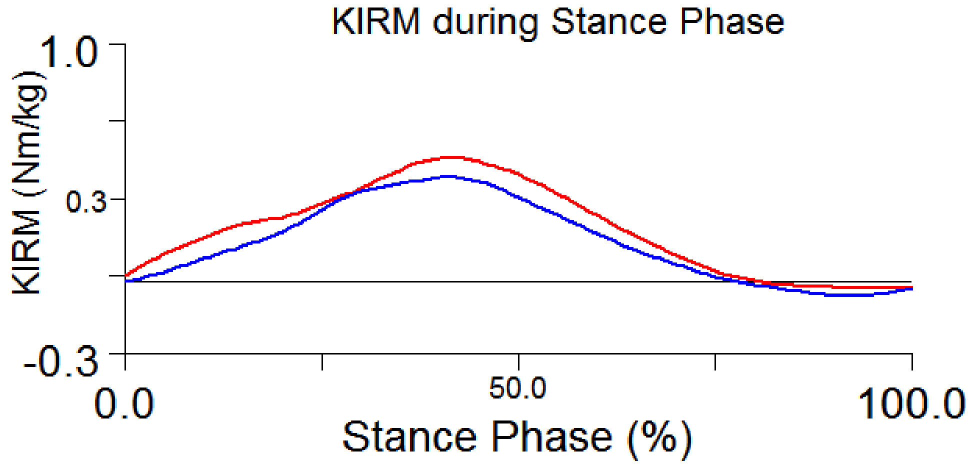


Figure 3-10: KIRM from a representative subject showing KIRM before (red) and after (blue) modified elliptical training.

A significant difference was observed in each of the knee moment variables in both the RFS and MFS trials between the C-PRE and I-PRE groups.

When comparing each of the groups during the RFS and MFS trials, the knee moments were lower in all groups, except for C-PRE, when subjects ran with a MFS rather than a RFS. There was no difference between RFS KFM and MFS KFM in the C-PRE group.

Figure 3-5 compares the KFM between each of the groups for each foot strike pattern. Except for modified elliptical training having no effect on MFS KFM, KFM increased in the RFS and MFS trials after training on either elliptical. It was also observed that there was a greater KFM increase after training on the non-modified elliptical as compared to training on the modified elliptical.

KAM in Figure 3-6 shows similar differences in the RFS trials and the MFS trials. For both foot strike patterns there was a significant decrease from C-PRE to C-POST and I-PRE to I-POST.

In Figure 3-7, which illustrates KIRM data for each group, a significant decrease was observed from C-PRE to C-POST in both foot strike patterns, and no change was observed between I-PRE and I-POST for either foot strike pattern.

Stride Frequency

SF was calculated for each of the groups. Table 3-8 displays the calculated SF values before being normalized. The values in Figure 3-11 have been normalized by subject leg length and treadmill velocity.

Table 3-8: SF descriptive statistics comparing group, foot strike, and time before normalizing for subject leg length and treadmill velocity.

			Mean	Standard Deviation	Minimum	Maximum	Range
Control	RFS	PRE	80.65	7.23	68.55	87.54	18.99
		POST	80.48	7.48	67.37	88.16	20.79
	MFS	PRE	81.58	7.26	68.83	88.90	20.07
		POST	81.35	7.88	68.13	90.22	22.09
Intervention	RFS	PRE	80.58	4.78	72.33	89.02	16.69
		POST	79.98	4.73	73.47	87.95	14.48
	MFS	PRE	81.73	5.28	71.11	89.84	18.74

		POST	81.02	4.94	72.65	89.09	16.44

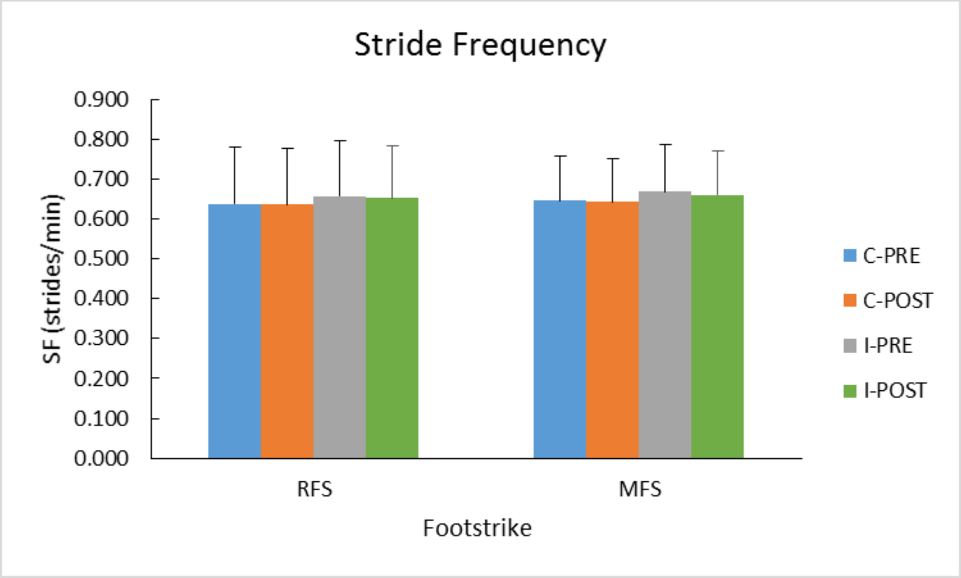


Figure 3-11: SF for each foot strike in each group. SF was normalized by leg length and speed of the treadmill.

There were no significant differences between groups when comparing SF. Between foot strikes, however, subjects ran with an increased SF when running with a MFS, with C-PRE, I-PRE, and I-POST being significant increases, as compared to running with a RFS. When comparing the groups within each foot strike, values trended towards a decrease in SF after either non-modified or modified elliptical training.

Chapter 4: Discussion

For each of the variables measured a significant difference was observed between the control group and intervention group before elliptical training. The subjects for both of these groups were drawn from the same population and the values before elliptical training would be expected to be similar in both groups. The difference in samples from the population is unexplained. For the following analysis, the results and effects of training on either elliptical trainer were not compared to each other. Any comparison between post non-modified elliptical training and post modified elliptical training were based on trends observed after training on either elliptical trainer.

Transitioning to MFS

The focus of this study was to teach natural RFS runners to run with a MFS pattern using a modified elliptical trainer. Since an ideal MFS runner would have a FIC of zero, subjects who have significant changes in FIC after training that tend closer to zero will have become more like a MFS runner. After two weeks of training on the modified elliptical there was a significant decrease in MFS FIC ($p = 0.005$) leading to the conclusion that training MFS was successful. This conclusion is further supported because there was no change in MFS FIC after training on the non-modified elliptical trainer. This was expected since the non-modified elliptical did not train subjects with the kinematics of a MFS pattern like the modified elliptical did. From this it can be argued that the decrease in MFS FIC as a result of the modified elliptical trainer is not just a result of training on an elliptical trainer, but instead was a result of task-specific training on the modified elliptical trainer.

FIC was not affected when subjects were instructed to run with their natural RFS after training on the modified elliptical trainer. This was to be expected since we were not training RFS and after much reinforcement of their habitual RFS pattern, it would take longer than two weeks to change their natural foot strike without instruction[11,17]. However, there was a significant decrease in RFS FIC after training on the non-modified elliptical trainer. A factor that affected this decrease could have been the kinematics on the non-modified elliptical which did not mimic normal running. These kinematic differences did not affect MFS FIC, but may have had an effect on RFS FIC.

As expected, when subjects ran with a MFS, FIC was lower than when they ran with their natural RFS. This supports what has already been seen when runners run with a MFS[6,7,8].

Impact Forces

Foot strike modification as a potential solution to decrease overuse running injuries has been used in the past[11,12,13,14]. This research supports that argument. When subjects run in a MFS pattern, VIP, VALR, and VILR were lower when compared to the same values during the execution of a RFS pattern. The only group where this was not true was the VIP before elliptical training where the VIP in RFS was lower than MFS. This does not come as a great surprise since subjects were naturally RFS runners and did not know previously how to run with a MFS. The fact that after modified elliptical training subjects decreased their VIP in MFS running below RFS running illustrates that training on the modified elliptical had an impact and that this impact was positive (with regard to potential injury reduction).

This reduction in impact forces after training on the modified elliptical was also evident when comparing MFS before and after modified elliptical training. After training on the modified elliptical trainer, VIP was significantly decreased ($p=<0.001$). Based on the decrease in MFS FIC after modified elliptical training, this decrease was also expected and supports what has already been seen in previous studies. Decreases in VALR and VILR were also expected, but instead no change occurred in VALR and VILR after modified elliptical training.

When comparing these conclusions to the data of subjects who trained on the non-modified elliptical there were similar results. MFS VIP and VILR significantly decreased and no change occurred in VALR. Based on those results, the decrease in MFS VIP that was observed after training on the modified elliptical may have been a result of elliptical training in general and not specifically training on the modified elliptical. This claim can further be supported because after non-modified elliptical training no change occurred in MFS FIC while there was a decrease in MFS FIC after modified elliptical training. It would be expected that since training on the non-modified did not have an effect on MFS running there would be no change in the impact forces. However, since there was an affect, the affect could have been a result of elliptical training in general. As a result, it becomes inconclusive as to whether the effects on the impact forces observed after modified elliptical training were a result of the modifications or just the fact of training on the elliptical.

Analyzing the impact forces in the RFS trials there were some expected results and some unexpected results. First, there was no change in VIP, VALR, or VILR as a result of modified elliptical training. This was to be expected since subjects were not RFS trained and there was no change in RFS FIC after modified elliptical training. After non-modified elliptical training, there was a decrease in RFS VIP, VALR, and VILR. With the decrease in RFS FIC, those decreases observed in the RFS impact forces were expected because studies showing a decrease in FIC have shown to also decrease impact forces[11,12,13,14].

Peak Knee Moments

Previous studies have shown that MFS runners have lower KFM and KAM than RFS runners while the effect of foot strike on KIRM has produced mixed results[2,50,51,52,53]. Thus those results would also be expected when comparing RFS and MFS, and this is indeed observed. In all groups, except before non-modified elliptical training where there was no change in KFM, there were decreased knee moments, supporting the findings of previous studies. When comparing the effect of elliptical training we see something quite interesting. KFM, after training on the non-modified elliptical, significantly increased in both the RFS ($p = <0.001$) and MFS ($p = <0.001$) trials. Analyzing the data after modified elliptical training a different affect was observed. RFS KFM increased after modified elliptical training, but MFS KFM did not change. It was expected that KFM would decrease after seeing a change in MFS FIC after modified elliptical training, but it seems that instead the training may have countered the potentially negative affect elliptical training may have on KFM. One explanation for an increase in KFM is that KFM is affected by a decrease in SF. In two studies that looked at the effect of step rate on joint kinematics, it was shown that KFM was increased as a result of a decrease in SF[53,54]. It appears that the decrease in SF, though not significant, may have affected this increase. However, this same decrease in SF also occurred in the MFS trials after modified elliptical training so that might not be the best explanation for the KFM increase. Consequently, a conclusion on what affect training on an elliptical may have on KFM cannot be made, but it can be concluded that training on the modified elliptical counteracts that potentially harmful affect.

There was a significant decrease in MFS KAM (p = <0.001) after modified elliptical training. This result for MFS KAM was expected since previous studies had shown lower KAM as runners began to adopt a MFS pattern[2,50]. Comparing this to MFS KAM after non-modified elliptical training, a similar decrease occurred. Therefore, there may be a training effect on KAM as a result of elliptical training. Analyzing the training effects on RFS KAM, similar results with RFS significantly decreasing after either non-modified or modified elliptical training. A decrease in RFS KAM after non-modified elliptical training was expected since there was a decrease in RFS FIC after non-modified elliptical training, but a decrease in RFS KAM after modified elliptical training was not expected. Thus, modified elliptical training that is biased toward a MFS pattern may be affecting more than just MFS running.

The results collected for KIRM are slightly more difficult to interpret. KIRM was previously studied by instructing RFS runners to run with a forefoot strike (FFS) and comparing the knee moments between RFS and FFS. This study showed an increase in KIRM in FFS runners as compared to RFS runners[52]. Another study compared the knee moments between subjects running with a RFS and running barefoot. While running barefoot does not guarantee a FFS, they did see subjects run more on their toes while running barefoot. The results they collected showed a decrease in KIRM in the barefoot runners as opposed to when they were running with a RFS in shoes[2,53]. In our experiment, KIRM was decreased in MFS compared to RFS in all groups. There was also a decrease in MFS KIRM, though not significant, after modified elliptical training, which would suggest that KIRM may be lower in MFS. However, MFS KIRM after non-modified elliptical training, which did not affect FIC after training, decreased MFS KIRM. Based on these results, it can be concluded that training on the modified elliptical did have an effect on a subject's gait, but it cannot be determined what affect training on an elliptical may have. This could be why mixed results have been obtained in other studies with regards to this variable. Switching focus over to the effect elliptical training had on RFS KIRM, after modified elliptical training RFS KIRM tended toward a decrease (not significant) and after non-modified elliptical training there was a significant KIRM decrease. These results are similar to what were observed in the MFS counterparts. Neither the non-modified or modified elliptical training trained RFS running, but a similar trend was seen in KIRM after training on either elliptical in the RFS and MFS trials. It can be theorized from this that elliptical training in general may affect KIRM of all running gait and not just KIRM of the running pattern that is being trained.

Stride Frequency

SF has been seen to be affected by foot strike with a greater SF in MFS running compared to RFS[7,44,45]. The data supports this theory as well. Subjects ran with a faster SF when running with a MFS then when they were running with their natural RFS. This was a result of landing with the foot closer to the body during MFS and ultimately decreasing the stride length and increasing SF[56].

When comparing groups within each foot strike pattern, results were unexpected. After training on either elliptical trainer, SF trended towards a decrease in both RFS and MFS. At first glance it may appear that foot strike contributed to the decrease in SF, however, the decrease also occurred in the RFS trials. It appears that elliptical training may have an effect on SF. This effect could be a result of the fixed stride length of the elliptical trainers. Both elliptical trainers used in this experiment had the same fixed stride length so it is logical that the same affect would occur after training on either elliptical. There are now elliptical trainers that have variable stride lengths and it would be intriguing to test whether changing the stride length during elliptical training had any effect on the stride frequency.

Elliptical Training Effect and Central Pattern Generator

It is important to reiterate that in this experiment the control group trained on a non-modified elliptical trainer that did not mimic the kinematics of RFS or MFS running and the intervention group trained on a modified elliptical trainer that more closely mimicked the kinematics of running, biased towards MFS running. Even with these distinct kinematic differences between the elliptical trainers, changes in multiple variables after training on either elliptical contain some similar trends.

C-POST Study Results		I-POST Study Results	
MFS	RFS	MFS	RFS
— FIC	↓ FIC	↓ FIC	— FIC
↓ VIP	↓ VIP	↓ VIP	— VIP
— VALR	↓ VALR	— VALR	— VALR
↓ VILR	↓ VILR	— VILR	— VILR
↑ KFM	↑ KFM	— KFM	↑ KFM
↓ KAM	↓ KAM	↓ KAM	↓ KAM
↓ KIRM	↓ KIRM	— KIRM	— KIRM
— SF	— SF	— SF	— SF

Figure 4-1: Comparison of the post training effects for both the control group and intervention group.

Focusing on changes that resulted from modified elliptical training, there was a decrease in MFS FIC and no change in RFS FIC illustrating that after training, subjects were better able to adopt a MFS pattern without affecting their natural RFS pattern. Most every other MFS variable was not affected by training except for MFS VIP and MFS KAM. When comparing this to the RFS trials after modified elliptical training, almost all of the variables, except for RFS KFM and RFS KAM, were unaffected. Seeing that KAM was similarly affected in both MFS and RFS is intriguing. A decrease in KAM was expected since an adoption of MFS had previously been shown to decrease KAM. However, RFS was not trained nor was it affected by the training so to see a similar decrease is curious. This KAM affect could be a result of elliptical training in general because a similar decrease was observed in KAM after non-modified elliptical training. Further studies would be needed to determine this.

Switching focus to the results after non-modified elliptical training, many more trends are observed. There was no change in MFS FIC which was expected since the non-modified elliptical was not training a MFS pattern. However, there was a decrease in RFS FIC which was not expected. Based on this decrease in FIC, most of the changes in the other variables are logical with there being decreases in VIP, VALR, VILR, KAM, and KIRM. The one variable that was unexpected was the increase in KFM. This increase may be an effect of elliptical training, however, because this similar increase was also observed after non-modified elliptical training in MFS KFM and after modified elliptical training in RFS KFM and MFS KFM (not significant, but trending towards an increase). Looking at the non-modified elliptical data side by side, a more curious thing is revealed. In all variables except for VALR, there was a similar decrease or increase in the RFS trials and the MFS trials. Again those changes in the RFS trials seem logical based on the decrease in RFS FIC, but the changes in the MFS trials do not because there was no change in MFS foot strike pattern after non-modified elliptical training. It is possible that elliptical training itself can affect the rhythmic oscillation controlling running and ultimately the central pattern generator. Research has shown that the central pattern generator can be altered but requires consistent sensory feedback[57]. Structured kinesthetic motor training on an elliptical provides that consistent repetitive movement making it plausible that the central pattern generator could have been altered after training on the non-modified elliptical. Now this immediately brings up the question of if elliptical training can affect the central pattern generator, why this similar affect was not also observed in the intervention group. There is no explanation for why that is the case. It could be that the constant toe-down footplate on the non-modified elliptical, while still having incorrect kinematics to normal running, had enough of a cognitive effect on the subjects to cause similar differences in these different variables. Further studies of testing different elliptical trainers or testing different footplate positions would need to be conducted to better understand the implications of these results.

Modified Elliptical Trainer Limitations

There were a couple limitations with this study. First, both elliptical trainers had a fixed stride length. Stride length varies between individuals as a result of many factors including leg length, and our modified elliptical trainer does not compensate for that. There was also a mechanical limitation that does not allow subjects to train at a self-selected speed on the modified elliptical trainer. This was a result of the large amount of torque on the flywheel produced when using the elliptical. As a result, subjects were required to train on the modified elliptical trainer at 1 mph. In future modifications, the amount of mass associated with the ski and the amount of torque on the flywheel will be reduced to allow subjects to train at their self-selected speed. As Bradford pointed out previously[37], the elliptical trainer was not able to mimic the ankle kinematics of walking/running 100%. This is especially prevalent during the toe-off phase of the gait cycle. This limitation will be considered when designing the next iteration.

Chapter 5: Conclusion

The focus of this study was to research the ability of using structured kinesthetic motor learning to teach natural RFS runners to run with a MFS pattern using a modified elliptical trainer. Secondarily, the effect of modified elliptical training on the ability to reduce impact loads, decrease knee moments, and increase stride frequency during running was determined. This alteration of foot strike using an elliptical trainer was chosen because it is a user-driven system that provides consistent and repetitive training of a desired movement.

After structured kinesthetic motor training on the modified elliptical trainer, there was a decrease in FIC when subjects were instructed to run with a MFS. This shows that the device was able to train and alter the mechanics of runners who desired to transition to a MFS running technique. The implications of this finding is that running gait, in this case foot strike patterns, can be altered using structured kinesthetic motor learning, which has not previously been found. Possibly leading to this method being more widely used in gait retraining as a result of its ability to provide consistent and repetitive training of a desired movement.

In the second goal of this study, modified elliptical training did not affect many of the variables that have shown to be affected by foot strike alteration when subjects ran with a MFS pattern. However, the few it did affect, VIP and KAM, decrease the probability of injury.

The more curious results were seen when looking at the post-training non-modified elliptical data lending the thought that elliptical training could have an effect on running gait and ultimately the central pattern generator. With the consistent sensory feedback gathered by the body during structured kinesthetic motor training, it is plausible that an alteration in the central pattern generator could have occurred, but further research as to why this was observed in the non-modified elliptical and not the more kinematically accurate modified elliptical is necessary before any conclusions can be drawn.

Future studies to be done include but are not limited to the following:

1. Investigate if learning retention has occurred by requiring the subjects to complete a follow-up gait analysis one or two months after testing.
2. Investigate if switching between a RFS and MFS camming profile is necessary. This can be tested by having one group train with the RFS and MFS camming profiles biased towards MFS, another group that trains with a varying MFS camming profile, and another group that trains with just a consistent MFS camming profile.
3. Investigate if the footplate being in the consistent toe-down phase on the non-modified elliptical had an effect. This could be done by having one group of subjects train on the non-modified elliptical, another group train on the modified elliptical with the footplate consistently in the toe-down phase, and another group training on the modified elliptical in a normal RFS pattern.
4. Test subjects on an elliptical trainer with the ability to change stride length to observe the affects that the fixed stride length on the elliptical trainers may have had on SF or other variables.

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Appendix A

Study Approval by Institutional Review Board

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TO: Peter Pidcoe
CC: Trisha Massenzo
Peter Pidcoe
Daniel Shull
FROM: IRB Panel A
RE: Peter Pidcoe ; IRB HM20001713_CR2 Investigation of modified footstrike training in normal runners

On 5/18/2016 this research study was ***approved for continuation*** by expedited review according to 45 CFR 46.108(b) and 45 CFR 46.109(e) and 45 CFR 46.110 by VCU IRB Panel A. This study is approved under Expedited category 4.

The information found in the electronic version of this study's smart form and uploaded documents now represents the currently approved study, documents, informed consent process, and HIPAA pathway (if applicable). Please see instruction box below for details on viewing the approved study.

This approval expires on 4/30/2017. Federal Regulations/VCU Policy and Procedures require continuing review prior to continuation of approval past that date. Continuing Review notices will be sent to you prior to the scheduled review.

If you have any questions, please contact the Office of Research Subjects Protection (ORSP) or the IRB reviewer(s) assigned to this study.

The reviewer(s) assigned to your continuing review will be listed in the History tab and on the continuing review workspace. Click on their name to see their contact information.

Attachment – Conditions of Approval

Conditions of Approval:
In order to comply with federal regulations, industry standards, and the terms of this approval, the investigator must (as applicable):

1. Conduct the research as described in and required by the Protocol.

2. Obtain informed consent from all subjects without coercion or undue influence, and provide the potential subject sufficient opportunity to consider whether or not to participate (unless Waiver of Consent is specifically approved or research is exempt).

3. Document informed consent using only the most recently dated consent form bearing the VCU IRB “APPROVED” stamp (unless Waiver of Consent is specifically approved).

4. Provide non-English speaking patients with a translation of the approved Consent Form in the research participant's first language. The Panel must approve the translated version.

5. Obtain prior approval from VCU IRB before implementing any changes whatsoever in the approved protocol or consent form, unless such changes are necessary to protect the safety of human research participants (e.g., permanent/temporary change of PI, addition of performance/collaborative sites, request to include newly incarcerated participants or participants that are wards of the state, addition/deletion of participant groups, etc.). Any departure from these approved documents must be reported to the VCU IRB immediately as an Unanticipated Problem (see #7).

6. Monitor all problems (anticipated and unanticipated) associated with risk to research participants or others.

7. Report Unanticipated Problems (UPs), including protocol deviations, following the VCU IRB requirements and timelines detailed in VCU IRB WPP VIII7):

8. Obtain prior approval from the VCU IRB before use of any advertisement or other material for recruitment of research participants.

9. Promptly report and/or respond to all inquiries by the VCU IRB concerning the conduct of the approved research when so requested.

10. All protocols that administer acute medical treatment to human research participants must have an emergency preparedness plan. Please refer to VCU guidance on http://www.research.vcu.edu/irb/guidance.htm.

11. The VCU IRBs operate under the regulatory authorities as described within:
a) U.S. Department of Health and Human Services Title 45 CFR 46, Subparts A, B, C, and D (for all research, regardless of source of funding) and related guidance documents.
b) U.S. Food and Drug Administration Chapter I of Title 21 CFR 50 and 56 (for FDA regulated research only) and related guidance documents.
c) Commonwealth of Virginia Code of Virginia 32.1 Chapter 5.1 Human Research (for all research).

Conditions of Approval (version 010507)

Appendix B

Matlab Source Code for calculating ground reaction forces

```
%Ground Reaction Force Program
%Objective:  Process force data in order to find VIP, VALR, and VILR
%Note:  Force data is in Newtons

clear all

%User enters data into the program
filename = input('Enter name of force data file with extension','s');
file = dlmread(filename,'\t',2,1);
len=length(file);

force = file(:,4);

%Code to determine the impact peak for each stride
clear high
k=1;
m=1;
for i=6:1:(length(force)-8);

  if force(i)> force(i-1)&& force(i)> force(i-2) && force(i)>force(i+1)&& force(i)<force(i+8)&&
force(i)>500 && m==1;
     high(k)= i;
     k=k+1;
     m=2;
  end
  if m==2 && i>(high(k-1))
     m=1;
  end
end
```

```
peak = force(high);
peaks = [transpose(high),peak];
VIP_supposed = [transpose(high(1:1:length(high))),peak(1:1:length(high))];

%Double check that only VIPs have been accounted for
for j=2:1:(length(VIP_supposed));

  group(j-1) = VIP_supposed(j,1)-VIP_supposed(j-1,1);

end

%Determine the average amount of points between impact peaks
stride = mean(group);

q=0;
for j=1:1:(length(VIP_supposed)-1);
  if (VIP_supposed(j+q+1,1)-VIP_supposed(j+q,1))<(stride-25)
     VIP(j,1) = VIP_supposed(j+q,1);
     VIP(j,2) = VIP_supposed(j+q,2);
     q=q+1;
  else
     VIP(j,1) = VIP_supposed(j+q,1);
     VIP(j,2) = VIP_supposed(j+q,2);
  end
end

%Code to determine the point of initial contact for each stride
g=1;
h=1;
for j=8:1:(length(force)-5);

  if (force(j)-force(j-1))> 1 && force(j)>10 && force(j-1)<10 && force(j)<force(j+1) &&
force(j)<force(j+2)&& force(j)<force(j+3)&& force(j)<force(j+4)&& h==1;
     start(g)= j;
     g=g+1;
     h=2;
  end
  if h==2 && j>(start(g-1))
     h=1;
  end
end
```

```
contact = force(start);
initial_contact = [transpose(start),contact];

%obtain range between initial contact and impact peak
if length(VIP)~=length(initial_contact);
 for j=2:1:(length(initial_contact));
     list(j-1) = initial_contact(j,1)-initial_contact(j-1,1);

  end
end

%Determines the average amount of points between landing
gait = mean(list);
corrected = zeros(length(VIP),2);

p=0;
for j=1:1:(length(corrected)-1);
  if (VIP(j+1,1)-VIP(j,1))>((gait*4)+20)
      corrected(j,1) = initial_contact(j+p,1);
      corrected(j,2) = initial_contact(j+p,2);
      p=p+4;
  elseif (VIP(j+1,1)-VIP(j,1))>((gait*3)+20)
      corrected(j,1) = initial_contact(j+p,1);
      corrected(j,2) = initial_contact(j+p,2);
      p=p+3;
  elseif (VIP(j+1,1)-VIP(j,1))>((gait*2)+20)
      corrected(j,1) = initial_contact(j+p,1);
      corrected(j,2) = initial_contact(j+p,2);
      p=p+2;
  elseif (VIP(j+1,1)-VIP(j,1))>(gait+20)
      corrected(j,1) = initial_contact(j+p,1);
      corrected(j,2) = initial_contact(j+p,2);
      p=p+1;
  else
      corrected(j,1) = initial_contact(j+p,1);
      corrected(j,2) = initial_contact(j+p,2);
  end

end
```

```
VIP = VIP(1:length(VIP)-1,:);
corrected = corrected(1:length(VIP),:);
dif = VIP(:,1) - corrected(:,1);
dif_per = round(dif*0.2);
highpoints = VIP(:,1)- dif_per;
lowpoints = corrected(:,1)+ dif_per;
range = [lowpoints,force(lowpoints),highpoints,force(highpoints)];

%average vertical loading rate
  %create x and y points for each range
n=1;
for j=1:1:(length(range));

  time{j}= (range(j,1):1:range(j,3));
  clear fp_array
  d=1;
  for i=1:1:(length(force));
     if range(j,1)== i && n==1
        n=2;
     end
     if n==2
        fp_array(d) = i;
        d=d+1;
     end
     if n==2 && i==range(j,3)
        n=1;
        break
     end
  end
   fp{j}= transpose(force(fp_array));

end

%Create the equation for each section
n=1;
for j=1:1:length(time)
  eqns = polyfit(time{j}*0.01,fp{j},1);
  slope(n)=eqns(1);
  n=n+1;
end
```

```
VALR = transpose(slope);

 %instantaneous vertical loading rate
d=1;
for j=1:1:(length(time));
   change = diff(fp{j});
   islope(j) = max(change./0.01);

end

VILR = transpose(islope);
```

Appendix C

Left Footplate Controller Program

```
PROGRAM
 PBOOT
 DETACH
 ATTACH MASTER0
 ATTACH SLAVE0 AXIS0 "L"
 PPU L8000
 AXIS0 EXC(5,-5) : REM set excess error limits (0.01 is about 5 deg of motor rotation, less than .1
for footplate)
 SET BIT8469: REM enable EXC response
 TLM L7 : REM set torque limit to +- 2 V
 REM Axis Gains values
 AXIS0 PGAIN 0.008
 AXIS0 IGAIN 0
 AXIS0 ILIMIT 0
 AXIS0 IDELAY 0
 AXIS0 DGAIN 0.0001
 AXIS0 DWIDTH 0
 AXIS0 FFVEL 0
 AXIS0 FFACC 0
 AXIS0 TLM 10
 AXIS0 FBVEL 0
 REM Axis Limits
 AXIS0 HLBIT 1
 AXIS0 HLDEC 100
 HLIM L3
 'SET BIT16144
 SET BIT16145
 CLR BIT16146
 SET BIT16148
 SET BIT16149
```

```
AXIS0 SLM(20,-20)
AXIS0 SLDEC 100
SLIM L3
SET BIT16150
SET BIT16151
REM MOTION PROFILE
REM the desired master acceleration
ACC 100
REM the desired master deceleration ramp
DEC 100
REM the desired master stop ramp (deceleration at end of move)
STP 250
REM the desired master velocity
VEL 10
REM the desired acceleration versus time profile.
JRK 0
JOG VEL L1
JOG ACC L25
JOG DEC L25
REM BEGIN HOMING SEQUENCE
CLR BIT136
clr bit137
clr bit0
clr bit1
clr bit2
clr bit3
clr bit1920
clr bit1921
PRINT "Press green button To start homing, press red button To stop at any time"
'
_MAIN1
IF (NOT BIT1 OR NOT BIT2) THEN SET BIT1920 REM RED BUTTON OR ANY EOT SWITCH
IF (BIT1920) THEN SET BIT8467
IF (BIT 1920) THEN CLR BIT136
IF (NOT BIT0 AND NOT BIT3) THEN SET BIT1921  REM 0001 GREEN BUTTON
IF (BIT1921 AND NOT BIT136) THEN GOTO HOMING
IF (BIT136 AND NOT BIT137) THEN GOTO CAMMING: REM IF BIT 136 (USER DEFINED = HOMING COMPLETE) IS SET, START CAMMING
IF (BIT8467) THEN CLR BIT136 REM IF A KILL ALL MOTION FLAG IS SET (8467) THEN CLEAR BIT 136 AND TURN THE CAM OFF
IF (BIT1921 AND BIT136 AND BIT137) THEN GOTO CHANGE
```

```
GOTO MAIN1
'
_HOMING
PRINT "BEGIN HOMING"
BIT798= 0 : REM CHECK JOG LIMITS WHEN JOGGING FWD/REV
JOG VEL L1 : REM SET JOG VELOCITY TO 1 REV/S
DRIVE ON L
CLR 8467
JOG FWD L
PRINT " JOGGING IN POSITIVE DIRECTION "
INH -792 : REM WAIT UNTIL MOTION HAS STOPPED
PRINT " POSITIVE LIMIT SWITCH FOUND "
CLR 8467 : REM CLEAR KILL ALL MOVES FLAG THAT IS SET WHEN A LIMIT IS REACHED
JOG REV L
PRINT " JOGGING IN NEGATIVE DIRECTION "
INH -792
PRINT " NEGATIVE LIMIT SWITCH FOUND "
PRINT " ZERO POSITION AT NEG SWITCH "
CLR 8467
JOG INC L6.18334
PRINT " MOVING TO OFFSET POSITION "
INH -792
PRINT " AT OFFSET POSITION"
JOG RES L0
RES L0
PRINT " ZERO POSITION REGISTER AT HOME POSITION "
SET BIT136
CLR BIT137
CLR BIT1921
clr bit1936
GOTO MAIN1
'
_CAMMING
AXIS0 EXC(5,-5) : REM set excess error limits (0.01 is about 5 deg of motor rotation, less than .1
for footplate)
DIM LA(4) : REM Dimension 4 long arrays
DWL 0.5
DIM LA0(69) : REM LA0 has 69 elements
DWL 0.5
DIM LA1(69)
DWL 0.5
```

```
 DIM LA2(69)
 DWL 0.5
 DIM LA3(69)
 DWL 0.5

LA0(0) = -1388
LA0(1) = -1940
LA0(2) = -2464
LA0(3) = -2969
LA0(4) = -3451
LA0(5) = -3894
LA0(6) = -4299
LA0(7) = -4659
LA0(8) = -4970
LA0(9) = -5237
LA0(10) = -5466
LA0(11) = -5645
LA0(12) = -5790
LA0(13) = -5815
LA0(14) = -5679
LA0(15) = -5404
LA0(16) = -5044
LA0(17) = -4583
LA0(18) = -4103
LA0(19) = -3588
LA0(20) = -3054
LA0(21) = -2521
LA0(22) = -2000
LA0(23) = -1490
LA0(24) = -1077
LA0(25) = -791
LA0(26) = -595
LA0(27) = -444
LA0(28) = -341
LA0(29) = -218
LA0(30) = -98
LA0(31) = 24
LA0(32) = 138
LA0(33) = 239
LA0(34) = 340
LA0(35) = 444
```

LA0(36) = 556
LA0(37) = 666
LA0(38) = 803
LA0(39) = 939
LA0(40) = 1077
LA0(41) = 1241
LA0(42) = 1425
LA0(43) = 1693
LA0(44) = 2005
LA0(45) = 2336
LA0(46) = 2672
LA0(47) = 3007
LA0(48) = 3356
LA0(49) = 3691
LA0(50) = 4028
LA0(51) = 4364
LA0(52) = 4611
LA0(53) = 4767
LA0(54) = 4782
LA0(55) = 4706
LA0(56) = 4553
LA0(57) = 4336
LA0(58) = 4060
LA0(59) = 3726
LA0(60) = 3330
LA0(61) = 2848
LA0(62) = 2272
LA0(63) = 1669
LA0(64) = 1058
LA0(65) = 428
LA0(66) = -201
LA0(67) = -804
LA0(68) = -1388

LA2(0) = -1388
LA2(1) = -1940
LA2(2) = -2464
LA2(3) = -2969
LA2(4) = -3451
LA2(5) = -3894
LA2(6) = -4299

LA2(7) = -4659
LA2(8) = -4970
LA2(9) = -5237
LA2(10) = -5466
LA2(11) = -5645
LA2(12) = -5790
LA2(13) = -5815
LA2(14) = -5679
LA2(15) = -5404
LA2(16) = -5044
LA2(17) = -4583
LA2(18) = -4103
LA2(19) = -3588
LA2(20) = -3054
LA2(21) = -2521
LA2(22) = -2000
LA2(23) = -1490
LA2(24) = -1077
LA2(25) = -791
LA2(26) = -595
LA2(27) = -444
LA2(28) = -341
LA2(29) = -218
LA2(30) = -98
LA2(31) = 24
LA2(32) = 138
LA2(33) = 239
LA2(34) = 340
LA2(35) = 444
LA2(36) = 556
LA2(37) = 666
LA2(38) = 803
LA2(39) = 939
LA2(40) = 1077
LA2(41) = 1241
LA2(42) = 1425
LA2(43) = 1693
LA2(44) = 2005
LA2(45) = 2336
LA2(46) = 2672
LA2(47) = 3007

```
LA2(48) = 3356
LA2(49) = 3691
LA2(50) = 4028
LA2(51) = 4364
LA2(52) = 4611
LA2(53) = 4767
LA2(54) = 4782
LA2(55) = 4706
LA2(56) = 4553
LA2(57) = 4336
LA2(58) = 4060
LA2(59) = 3726
LA2(60) = 3330
LA2(61) = 2848
LA2(62) = 2272
LA2(63) = 1669
LA2(64) = 1058
LA2(65) = 428
LA2(66) = -201
LA2(67) = -804
LA2(68) = -1388

DIM LV(6)
 LV0=0
 LV3=100
 LV4=0

 PRINT "SLOWLY MOVE FLYWHEEL FORWARD UNTIL THE FOOTPLATES BEGIN MOVING"
 INTCAP AXIS0 10 : REM arms capture of axis0 position when HS inp 4 rises (designated by 10)
 INH 777 : REM wait for flag 777 to be set (flag 777 is set when inp 4 trips intcap)
 ENC1 RES -2912 : REM resets encoder to -3700 so it is zero at BDC on the right.
 set bit 138
 PRINT "Index detected. Encoder reset."
 CAM DIM L1 : REM Define 1 cam segments
 CAM SEG L(0,10000,LA0) : REM Define cam segment range and source
 CAM SCALE L(1/1000) : REM scales cam output back to revolutions
 CAM SRC L1 : REM Define cam source as ENC1
 CAM SRC RES : REM resets the cam source to 0
 SET BIT137
 '
 _loop
```

```
IF  (P6160 = 0) THEN CAM ON L
IF  (BIT790) THEN GOTO MAIN1: REM Start camming
GOTO loop
'
_CHANGE
PRINT "Change Left Footplate Pattern"
INH 3
DIM DV(2)
DIM $V(2,7)
PRINT "Which Program?"
PRINT "1 Normal Camming"
PRINT "2 Attenuated Camming"
PRINT "3 Auto Attenuation"
PRINT "4 Standing Pertubation"
PRINT "5 incremented/decremented camming"
PRINT "6 closed loop camming"
PRINT "7 MFS Training Session"
'
INPUT; $V0
PRINT $V0
LV4 = VAL($V0)
PRINT "LV4=";LV4
'
IF (LV4=1) THEN PRINT "1 Normal Camming, BACK TO MAIN PROGRAM"
IF (LV4=2) THEN PRINT "2 Attenuated Camming"
IF (LV4=3) THEN PRINT "3 Auto Attenuation"
IF (LV4=4) THEN PRINT "4 Standing Pertubation"
IF (LV4=5) THEN PRINT "5 incremented/decremented camming"
IF (LV4=6) THEN PRINT "6 closed loop camming"
IF (LV4=7) THEN PRINT "7 MFS Training Session"

IF (LV4=1) THEN GOTO MAIN1
IF (LV4=2) then goto ATT
IF (LV4=3) then goto AUTO
IF (LV4=4) then goto SP
IF (LV4=5) then goto INCREMENT
IF (LV4=6) then goto CLOSED
IF (LV4=7) then goto MFS

PRINT "ERROR! BACK TO MAIN PROGRAM!"
GOTO MAIN1
```

```
_MFS

PRINT "TRAINING SESSION"

FOR LV2 = 0 TO 68 STEP 1
   LA1(LV2) = LA0(LV2)
NEXT

 LA2(1)=-1405.7
 LA2(2)=-1425.35
 LA2(3)=-1447.3
 LA2(4)=-1471.2
 LA2(5)=-1496.3
 LA2(6)=-1521.45
 LA2(7)=-1545.3
 LA2(8)=-1566.55
 LA2(9)=-1584.1
 LA2(10)=-1597.1
 LA2(11)=-1605.3
 LA2(12)=-1609
 LA2(13)=-1609.4
 LA2(14)=-1607.05
 LA2(15)=-1598.55
 LA2(16)=-1581.6
 LA2(17)=-1556.55
 LA2(18)=-1525.4
 LA2(19)=-1491.3
 LA2(20)=-1457.65
 LA2(21)=-1400
 LA2(22)=-1300
 LA2(23)=-1200
 LA2(24)=-1070

PRINT "Which Training Session is this?"

INPUT; $V0

LV4=VAL($V0)
PRINT "LV4=";LV4
```

```
IF (LV4=1) THEN PRINT "Training Session 1"
IF (LV4=2) THEN PRINT "Training Session 2"
IF (LV4=3) THEN PRINT "Training Session 3"
IF (LV4=4) THEN PRINT "Training Session 4"
IF (LV4=5) THEN PRINT "Training Session 5"
IF (LV4=6) THEN PRINT "Training Session 6"
IF (LV4=7) THEN PRINT "Training Session 7"
IF (LV4=8) THEN PRINT "Training Session 8"

IF (LV4=1) THEN GOTO TS1
IF (LV4=2) THEN GOTO TS2
IF (LV4=3) THEN GOTO TS3
IF (LV4=4) THEN GOTO TS4
IF (LV4=5) THEN GOTO TS5
IF (LV4=6) THEN GOTO TS6
IF (LV4=7) THEN GOTO TS7
IF (LV4=8) THEN GOTO TS8

_TS1
CLR 8467
CAM ON AXIS0

REM Start RFS
PRINT "RFS1"

FOR LV1 = 0 TO 240 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA1(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS1"
FOR LV1 = 241 TO 420 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA2(LV2)
  NEXT

DWL .87
```

```
NEXT

REM Transitions to RFS
PRINT "RFS2"
FOR LV1 = 421 TO 600 STEP 1
    FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA1(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS2"
FOR LV1 = 601 TO 780 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA2(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to RFS
PRINT "RFS3"
FOR LV1 = 781 TO 960 STEP 1
    FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA1(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS3"
FOR LV1 = 961 TO 1200 STEP 1
    FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA2(LV2)
  NEXT

DWL .87
NEXT
```

```
GOTO COMPLETE

_TS2
CLR 8467
CAM ON AXIS0

REM Start RFS
PRINT "RFS1"

FOR LV1 = 0 TO 240 STEP 1
 FOR LV2 = 0 TO 68 STEP 1
   LA0(LV2) = LA1(LV2)
 NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS1"
FOR LV1 = 241 TO 480 STEP 1
 FOR LV2 = 0 TO 68 STEP 1
   LA0(LV2) = LA2(LV2)
 NEXT

DWL .87
NEXT

REM Transitions to RFS
PRINT "RFS2"
FOR LV1 = 481 TO 720 STEP 1
 FOR LV2 = 0 TO 68 STEP 1
   LA0(LV2) = LA1(LV2)
 NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS2"
FOR LV1 = 721 TO 960 STEP 1
 FOR LV2 = 0 TO 68 STEP 1
```

```
      LA0(LV2) = LA2(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to RFS
PRINT "RFS3"
FOR LV1 = 961 TO 1200 STEP 1
    FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA1(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS3"
FOR LV1 = 1201 TO 1440 STEP 1
    FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA2(LV2)
  NEXT

DWL .87
NEXT
GOTO COMPLETE

_TS3
CLR 8467
CAM ON AXIS0

REM Start RFS
PRINT "RFS1"

FOR LV1 = 0 TO 300 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA1(LV2)
  NEXT

DWL .87
NEXT
```

```
REM Transitions to MFS
PRINT "MFS1"
FOR LV1 = 301 TO 660 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA2(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to RFS
PRINT "RFS2"
FOR LV1 = 661 TO 960 STEP 1
    FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA1(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS2"
FOR LV1 = 961 TO 1320 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA2(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to RFS
PRINT "RFS3"
FOR LV1 = 1321 TO 1620 STEP 1
    FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA1(LV2)
  NEXT

DWL .87
NEXT
```

```
REM Transitions to MFS
PRINT "MFS3"
FOR LV1 = 1621 TO 1800 STEP 1
    FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA2(LV2)
  NEXT

DWL .87
NEXT
GOTO COMPLETE

_TS4
CLR 8467
CAM ON AXIS0

REM Start RFS
PRINT "RFS1"

FOR LV1 = 0 TO 240 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA1(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS1"
FOR LV1 = 241 TO 720 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA2(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to RFS
PRINT "RFS2"
FOR LV1 = 721 TO 960 STEP 1
    FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA1(LV2)
```

```
  NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS2"
FOR LV1 = 961 TO 1380 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA2(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to RFS
PRINT "RFS3"
FOR LV1 = 1381 TO 1620 STEP 1
    FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA1(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS3"
FOR LV1 = 1621 TO 1800 STEP 1
    FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA2(LV2)
  NEXT

DWL .87
NEXT
GOTO COMPLETE

_TS5
CLR 8467
CAM ON AXIS0

REM Start RFS
```

```
PRINT "RFS1"

FOR LV1 = 0 TO 180 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA1(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS1"
FOR LV1 = 181 TO 720 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA2(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to RFS
PRINT "RFS2"
FOR LV1 = 721 TO 900 STEP 1
    FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA1(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS2"
FOR LV1 = 901 TO 1440 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA2(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to RFS
```

```
PRINT "RFS3"
FOR LV1 = 1441 TO 1620 STEP 1
    FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA1(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS3"
FOR LV1 = 1621 TO 1800 STEP 1
    FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA2(LV2)
  NEXT

DWL .87
NEXT
GOTO COMPLETE

_TS6
CLR 8467
CAM ON AXIS0

REM Start RFS
PRINT "RFS1"

FOR LV1 = 0 TO 120 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA1(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS1"
FOR LV1 = 121 TO 780 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA2(LV2)
  NEXT
```

```
DWL .87
NEXT

REM Transitions to RFS
PRINT "RFS2"
FOR LV1 = 781 TO 900 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
   LA0(LV2) = LA1(LV2)
 NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS2"
FOR LV1 = 901 TO 1500 STEP 1
 FOR LV2 = 0 TO 68 STEP 1
   LA0(LV2) = LA2(LV2)
 NEXT

DWL .87
NEXT

REM Transitions to RFS
PRINT "RFS3"
FOR LV1 = 1501 TO 1620 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
   LA0(LV2) = LA1(LV2)
 NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS3"
FOR LV1 = 1621 TO 1800 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
   LA0(LV2) = LA2(LV2)
 NEXT
```

```
DWL .87
NEXT
GOTO COMPLETE

_TS7
CLR 8467
CAM ON AXIS0

REM Start RFS
PRINT "RFS1"

FOR LV1 = 0 TO 60 STEP 1
 FOR LV2 = 0 TO 68 STEP 1
   LA0(LV2) = LA1(LV2)
 NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS1"
FOR LV1 = 61 TO 780 STEP 1
 FOR LV2 = 0 TO 68 STEP 1
   LA0(LV2) = LA2(LV2)
 NEXT

DWL .87
NEXT

REM Transitions to RFS
PRINT "RFS2"
FOR LV1 = 781 TO 840 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
   LA0(LV2) = LA1(LV2)
 NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS2"
```

```
FOR LV1 = 841 TO 1560 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA2(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to RFS
PRINT "RFS3"
FOR LV1 = 1561 TO 1620 STEP 1
    FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA1(LV2)
  NEXT

DWL .87
NEXT

REM Transitions to MFS
PRINT "MFS3"
FOR LV1 = 1621 TO 1800 STEP 1
    FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA2(LV2)
  NEXT

DWL .87
NEXT
GOTO COMPLETE

_TS8
CLR 8467
CAM ON AXIS0

REM Start MFS
PRINT "MFS"

FOR LV1 = 0 TO 1800 STEP 1
  FOR LV2 = 0 TO 68 STEP 1
      LA0(LV2) = LA2(LV2)
  NEXT
```

```
DWL .87
NEXT
GOTO COMPLETE

_COMPLETE
SET 8467
PRINT "1: Training Session is Over"
PRINT "2: Complete Another Training Session"

INPUT; $V0
LV5=VAL($V0)


IF (LV5=1) THEN PRINT "Training Session is Over"
IF (LV5=2) THEN PRINT "Complete another Training Session"

IF (LV5=1) THEN GOTO MAIN1
IF (LV5=2) THEN GOTO MFS

ENDP
```

Appendix D

Emergency Stop Program

```
PROGRAM
'Program 3 - emergency stop
'TODO: edit your program here
PBOOT
_stop
If (BIT0 AND NOT BIT1 AND NOT BIT2 AND NOT BIT3) THEN SET BIT1920
IF BIT1920 THEN set bit 8467
goto stop
ENDP
```

Vita

Daniel S. Shull was born on August 4, 1992, in Indianapolis, Indiana. He graduated from Henry M. Jackson High School, Mill Creek, Washington in 2010. He received his Bachelor of Science in Bioengineering from Santa Clara University in 2014 and subsequently began graduate school in Biomedical Engineering, graduating with a Master of Science in Biomedical Engineering from Virginia Commonwealth University in May 2017.