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The Effect of Good Form Running Gait Retraining on Lower Extremity Kinematics and Ground Reaction Forces

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Abstract

Running is a popular activity for those trying to get in shape, stay fit, and improve overall health. As running has increased in popularity over the past couple of decades, so has the number of running related injuries. (Higginson, 2009; Statistics and Research, 2016). Interest in running gait research has also increased to address and understand the running related injuries. In addition to reducing injuries, the search for an optimal running form that will improve efficiency is being pursued (Davis, 2005). Good Form Running has become an increasingly popular school of running that seeks to fulfill these needs, but its effects on the body have yet to be studied in totality. The objective of this pilot study was to contribute to the field of running biomechanics by conducting a quantitative comparison between common form running and Good Form Running. This work focused on sagittal plane lower extremity kinematics and ground reaction forces. This research employs both empirical and computational methods beginning with ground reaction force data and motion capture data of runners and is the initial effort to examine the difference between common form running and Good Form Running.

Data was collected on 12 healthy common form runners at a self-selected training pace before gait retraining, after gait retraining, and one month after gait retraining using Vicon 3D motion capture and AMTI in-ground force plates. After processing all of the participant data and calculating critical variables, statistical analysis was executed using repeated measures ANOVA and multivariate analysis. Statistical analysis revealed significant differences in loading rate, minimum horizontal ground reaction force, knee angle at contact, and ankle angle at contact. Between the first and last data collection, the mean loading rate decreased by 50.3%, mean minimum horizontal ground reaction force decreased by 21.6%, mean knee flexion increased by 29.5%, and the ankle went from dorsiflexed to plantar flexed at initial contact. A large decrease in

loading rate has been associated with a reduction in risk for injury and may indicate the benefits of switching to Good Form Running (Hreljac, Marshall, & Hume, 2000; Novacheck, 1998; van Gent, et al., 2012).

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1 Introduction

Running is a popular activity for those trying to get in shape, stay fit, and improve overall health. Still, like any physical sport, the benefits of running come with a risk for injury. The most common type of injuries runners acquire are overuse injuries (Hreljac, Marshall, & Hume, 2000). Stress fractures, plantar fasciitis, and tendonitis are only a few of the multitude of overuse injuries that recreational and competitive runners struggle (Hreljac, Marshall, & Hume, 2000). Almost all of these injuries can be derived from poor running form, inadequate shoes, or training conditions (Dixon & Batt, 2000; Daoud, et al., 2012; Hreljac, Marshall, & Hume, 2000; Luks, 2015; Nigg, 1985; van Gent, et al., 2012). Of these factors, running form is the most difficult to change and do so correctly (Dugan & Bhat, 2005; Heiderscheit, 2011). To address this, runners have searched for an ideal running form and popular running styles have emerged, such as Chi Running, Pose Method, and Good Form Running (Miller, 2016; Goss & Gross, 2012).

After running the same way for years, learning a new running style requires running gait retraining and disciplined practice to ensure proper adaptation and reduce risk of injury (Davis, 2005; Heiderscheit, Chumanov, Michalski, Wille, & Ryan, 2011). Gait retraining has shown to be beneficial in a clinical setting for pain reduction and rehabilitation; and is now being utilized as a means to prevent injury and improve performance in athletes (Crowell & Davis, 2011; Davis, 2005; De Wit, De Clercq, & Aerts, 2000). Previous studies have observed the biomechanics of Chi Running and Pose Method gait retraining, but the difference between Good Form Running and common form running has yet to be explored (Arendse, et al., 2004; Goss & Gross, 2012; Goss & Gross, 2013; Miller, 2016). Good Form Running (GFR) is a school of running founded by Curt Munson and John Benedict in 2006 that was created to reduce risk of injury and increase efficiency to make running easier on the body (Playmakers, 2016). While common form running is characterized by heel striking, over striding, and a slouched posture, GFR focuses on a teaching of proper trunk posture, mid-foot strike, increased cadence, and body lean. The purpose of this pilot study was to quantify differences in sagittal plane kinematics and ground reaction forces between common form running and Good Form Running on the same individual using a one-month gait retraining.

2 Background

Running is a very complex movement that requires the entire body to work in synchronicity to keep moving forward. The movement of running is easiest to understand when broken down into a single gait cycle. Like walking, the running gait cycle is made up of a stance and swing phase depicted in Figure 1 (Dugan & Bhat, 2005; Novacheck, 1998). This description of running gait is an industry standard.

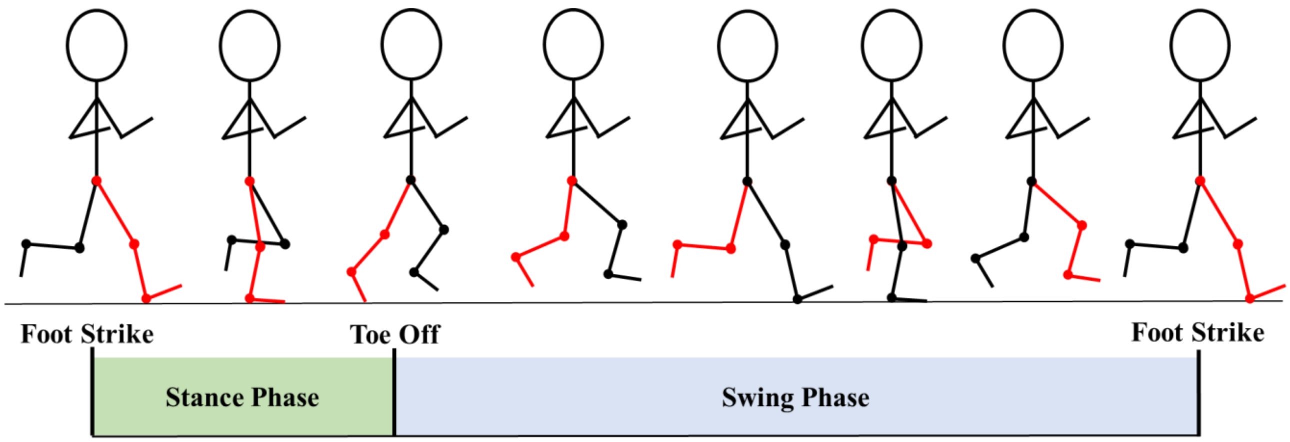

Figure 1: Running Gait Cycle

The gait cycle begins with initial contact of one foot and ends with the subsequent initial contact of the same foot. Stance phase begins with the initial contact of one foot and ends when that same foot leaves the ground, denoted as toe off. Stance phase can also be separated into periods of energy absorption and generation (Novacheck, 1998). Absorption occurs during the beginning of stance phase and appears to be related to the velocity of the center of mass decelerating as the foot strikes the ground, also referred to as braking (Novacheck, 1998). Generation occurs as the foot is pushing off the ground and the center of mass accelerates, also referred to as propulsion (Novacheck, 1998). During stance phase the planted leg works to absorb impact forces and propel the body upward and forward (Nicola & Jewison, 2012). Swing phase begins when the foot that was planted during stance phase leaves the ground and ends when the same foot contacts the ground again. The swing phase of running is what differs the most from walking as it includes two periods of float, where both feet are off the ground at the same time (Dugan & Bhat, 2005; Novacheck, 1998). This float occurs at the beginning and end of the swing phase.

The stance phase is a major focus when analyzing running because it is where the initial contact of a gait cycle occurs. The initial contact of stance phase is commonly called a foot strike. There are three types of foot strike patterns: rear foot, midfoot, and forefoot (Nicola & Jewison, 2012). A vast majority of distance runners use a rear foot strike pattern, much like walking, where the heel makes initial contact with the ground (Novacheck, 1998). A forefoot strike is when the ball of the foot hits the ground first and a midfoot strike falls in between a rear foot and forefoot strike (Daoud, et al., 2012).

Stride length, step length, and cadence are also terms used to describe running gait (Dugan & Bhat, 2005). The length of one gait cycle is called the stride length while the distance between initial contact of one foot to the initial contact of the opposite foot is step length. Cadence is the tempo of running and is the number of steps per unit time, usually steps per minute. Many studies have been conducted to observe how making acute changes to running form, such as altering cadence, stride length, or foot strike pattern, affect running biomechanics (Chumanov, Wille, Michalski, & Heiderscheit, 2012; Giandolini, et al., 2012; Heiderscheit, 2011; Lieberman, Warrener, Wang, & Castillo, 2015; Stearne, Alderson, Green, Donnelly, & Rubenson, 2014; Wellenkotter, Kernozek, Meardon, & Suchomel, 2014).

2.1 Biomechanics

The biomechanics of the running gait cycle are studied by measuring kinematics and kinetics. Kinematics is a branch of biomechanics concerned with the position of segments and joints as well as their velocities and accelerations and kinetics is the branch that concentrates on the forces associated with those movements (Dugan & Bhat, 2005). The key lower extremity kinematic variables are ankle, knee, and hip angles, forces, and moments (Dugan & Bhat, 2005; Nicola & Jewison, 2012). Lower extremity kinetic variables include forces, moments, and powers of lower extremity joints and ground reaction forces (Dugan & Bhat, 2005; Nicola & Jewison, 2012).

The lower extremity movements of runners occur mainly in the sagittal plane and are minimal in the coronal and transverse planes for healthy runners (Novacheck, 1998). Three-dimensional analysis more accurately describes joint motion, and is helpful for clinicians looking for gait abnormalities (Dugan & Bhat, 2005). Two-dimensional analysis, in the plane where a vast majority of joint movement occurs, allows for a gross inspection of running form (Dugan & Bhat, 2005). Wille, Lenhart, Wang, Thelen, & Heiderscheit (2014) concluded that key sagittal plane kinematics could also be used to estimate kinetic metrics associated with running injury, like foot angle at initial contact and distance between center of mass and heel at initial contact being used to estimate joint moments and loading rate. When lower extremity kinematics are observed in only the sagittal plane, joint movements are simplified to flexion/dorsiflexion (decreasing joint angles) and extension/plantarflexion (increasing joint angles) (Novacheck, 1998). Sagittal plane joint angles are dependent on running form and speed (Dugan & Bhat, 2005). Joint range of motion increases as speed increases to reduce vertical displacement of the center of mass (Dugan & Bhat, 2005; Novacheck, 1998). Since the maximum and minimum joint angles vary depending on the speed and flexibility of each individual, they are not important parameters in comparing running forms (Dugan & Bhat, 2005; Nicola & Jewison, 2012; Novacheck, 1998).

Ground reaction forces are the external forces that result from a body in motion coming in contact with the ground. The magnitude and shape of vertical and horizontal (fore-aft) ground reaction forces are dependent on running speed and foot strike pattern (Dugan & Bhat, 2005; Lieberman, Warrener, Wang, & Castillo, 2015). Increased running speed is associated with a greater peak vertical ground reaction force and a greater range between maximum and minimum fore-aft ground reaction forces (Lieberman, Warrener, Wang, & Castillo, 2015). Studies on foot strike pattern and ground reaction forces have observed a correlation between rear foot strikers and an additional peak at the beginning of the vertical ground reaction force but smooth peaks in horizontal ground reaction forces (Cavanagh & Lafortune, 1980; Daoud, et al., 2012; Giandolini, et al., 2012; Lieberman, et al., 2010; Lieberman, Warrener, Wang, & Castillo, 2015; Shih, 2013). These same studies observed only one peak in vertical ground reaction forces for midfoot and forefoot strikers, and two peaks in the energy absorption portion of horizontal ground reaction forces.

The vertical ground reaction force graph in Figure 2 shows an initial impact peak before the maximum peak, referred to as the impact transient (Larson, 2011). The impact transient is commonly seen in rear foot strikers and is explained as a stiffness of the lower leg that occurs when the ankle is dorsiflexed, the toes are pointed up, and the foot lands in front of the knee, resulting in overstriding (Daoud, et al., 2012; Nicola & Jewison, 2012). The vertical ground reaction force graph in Figure 3 shows only one peak, commonly seen in midfoot or forefoot strikers. The lack of an impact transient is presumed to be the result of the ankle and knee being more spring like instead of rigid (Daoud, et al., 2012; Dugan & Bhat, 2005; Nicola & Jewison, 2012).

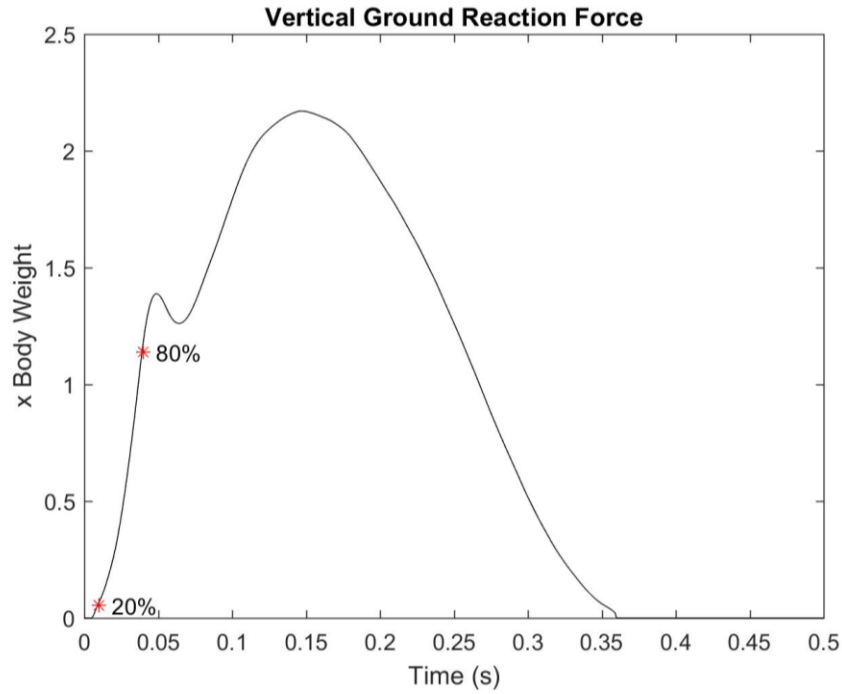

Figure 2: Vertical Ground Reaction Force with Impact Transient (20% and 80% of first peak marked for calculation of loading rate)

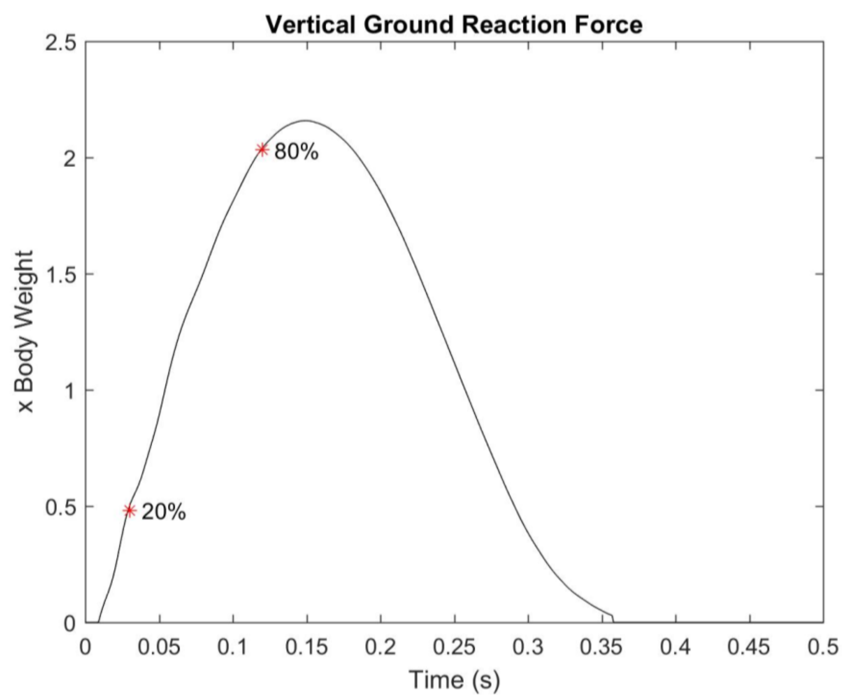

Figure 3: Vertical Ground Reaction Force without Impact Transient
(20% and 80% of only peak marked for calculation of loading rate)

Loading rate is a significant variable when observing ground reaction forces because of its relationship to overuse injuries; greater loading rate being associated with greater risk of injury (Daoud, et al., 2012; Larson, 2011). For this study, the loading rate is the same as that used in literature and is calculated as the positive slope of the vertical ground reaction force between 20% and 80% of the first or only peak (Daoud, et al., 2012; Davis, Bowser, & Mullineaux, 2015). With the 20% and 80% marked in Figure 2 and Figure 3, it can be seen that the slope between the two points is much greater with the impact transient than without. The loading rate with the impact transient in Figure 2 is calculated to be 43.4 times body weight per second (BW/s) and the loading rate without the impact transient in Figure 3 is 20.7 BW/s. This is an impact rate reduction of more than 50%.

The fore-aft ground reaction force illustrates the periods of energy absorption, referred to as braking, and energy generation, referred to as propulsion, that occur during the stance phase (Novacheck, 1998). These events can be observed in Figure 4 where the negative values indicate braking, and the positive values indicate propulsion (Munro, Miller, & Fuglevand, 1987). The amplitude and shape of the fore-aft ground reaction force is dependent on speed and foot strike pattern respectively (Boyer, Rooney, & Derrick., 2014; Cavanagh & Lafortune, 1980).

The fore-aft ground reaction force in Figure 4 is from a rear foot striker with one negative peak for braking, and one positive peak for propulsion. This indicates that the center of mass of the body starts posterior of the ankle and moves anterior of the ankle as the foot shifts from heel to toe (Boyer, Rooney, & Derrick., 2014). The fore-aft ground reaction force shown in Figure 5 is from a typical midfoot striker, with an additional braking peak. This double peak has been explained as a quick change in the body's center of mass as it moves from anterior of the ankle, where the ankle is plantarflexed at contact, to posterior of the ankle, where the ankle dorsiflexes slightly after contact (Boyer, Rooney, & Derrick., 2014). The ankle becomes dorsiflexed right after contact so the heel can lower to the ground and increase contact surface area of the foot to help absorb impact forces (Dixon & Batt, 2000).

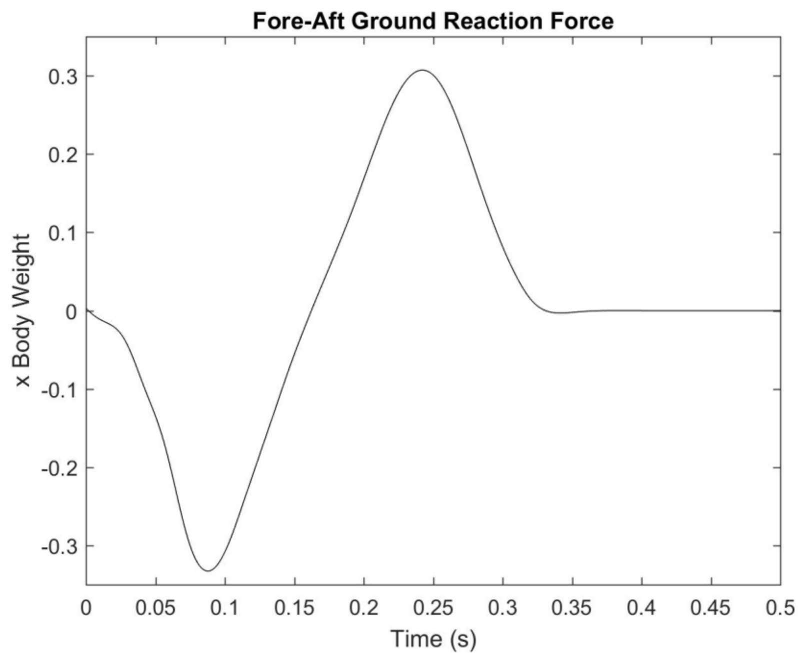

Figure 4: Fore-Aft Ground Reaction Force of Rear Foot Striker

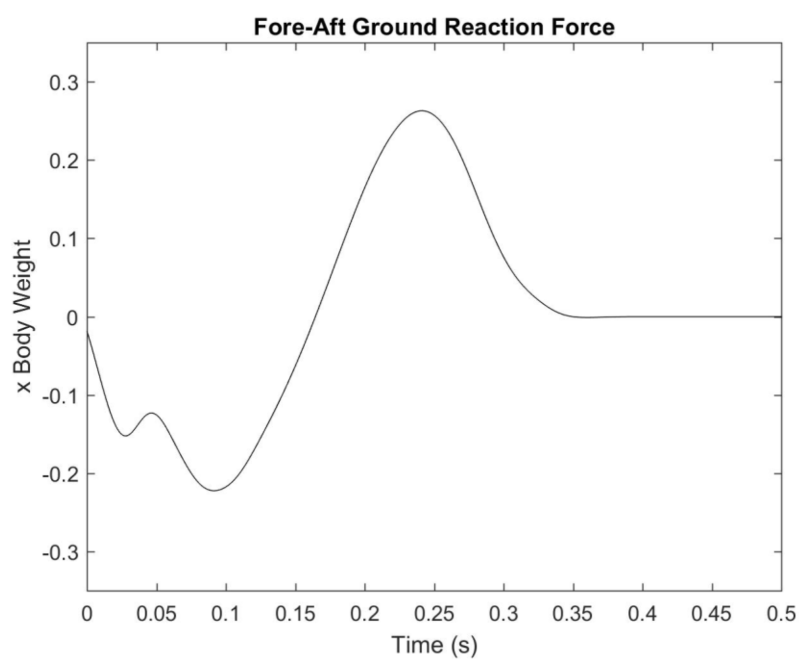

Figure 5: Fore-Aft Ground Reaction Force of Midfoot Striker

2.2 Methods of Modeling

Many tools have been developed to assess running gait motion and forces. High speed video analysis and motion capture systems are used to evaluate segment and joint positions, velocities, and accelerations, while force plates measure ground reaction forces and center of pressure locations (Fellin, Manal, & Davis, 2010; Higginson, 2009; Riley, et al., 2008). The quantification of body segment movements is most commonly collected using a motion capture system with marker identification (Higginson, 2009). These systems use passive or active markers placed on anatomical landmarks by a skilled operator to define body segments (Higginson, 2009). The major limitations of motion capture systems are that they are costly, require a trained operator to place markers consistently, and require a controlled capture volume (Higginson, 2009). High speed video analysis is less expensive and portable but it relies on edge detection of segments instead of anatomical markers (Higginson, 2009).

Force analysis is most commonly performed using force plates placed in the floor, called in-ground force plates, or under the belt of an instrumented treadmill (Fellin, Manal, & Davis, 2010; Higginson, 2009; Riley, et al., 2008). In-ground force plates allow for overground running, which is most familiar to recreational and competitive runners, but using them typically involves participants running on a short runway and collecting only one gait cycle at a time (Higginson, 2009; Riley, et al., 2008). Instrumented treadmills are convenient because running speed can be controlled and multiple consecutive gait cycles can be collected. However, studies have shown that running on treadmills alters foot strike pattern and therefore are not the best for analyzing a participant’s natural running gait (Fellin, Manal, & Davis, 2010). In-ground force plates are typically small and require proper foot placement that can make data collection challenging. Still, in-ground force plates are the better choice for studying natural running gait and examining the effects of gait retraining (Fellin, Manal, & Davis, 2010). Using these systems in conjunction allows for a comprehensive analysis of segment position and ground reaction forces for overground running.

2.3 Injuries

For recreational and competitive runners, injuries are a known risk. A major motivation for studying the biomechanics of running is to reduce this risk (Heiderscheit, 2011). Overuse injuries are the most common type of injuries runners face, and occur when a structure of the musculoskeletal system is strained by repetitive loading without proper time to heal (Hreljac, Marshall, & Hume, 2000; van Gent, et al., 2012). These injuries can be derived from poor running form, inadequate shoes, training conditions, training intensity or changes in training (Dixon & Batt, 2000; Daoud, et al., 2012; Hreljac, Marshall, & Hume, 2000; Luks, 2015; Nigg, 1985; van Gent, et al., 2012). Running form is the biggest contributor of these factors, but includes a vast number of variables that could lead to injury (Dugan & Bhat, 2005; Heiderscheit, 2011). It is difficult to study what causes these injuries specifically because after the injury occurs runners make changes to their running form to reduce their pain (Agresta & Brown, 2015; Davis, 2005; Novacheck, 1998). Also, if a runner continues to run while injured they tend to put less load on the injured leg, causing a compensatory loading that can lead to injuries in both legs (Hreljac, Marshall, & Hume, 2000; Novacheck, 1998).

Despite this challenge, researchers have created methods to capture key characteristics associated with overuse injuries. Hreljac et al. studied the difference in gait analysis variables between runners that had never been injured and runners that had sustained at least one overuse injury (Hreljac, Marshall, & Hume, 2000). They concluded that runners with lower loading rates have a reduced risk for injury (Hreljac, Marshall, & Hume, 2000). Other studies categorized participants by injury history because it has been found that those with previous lower extremity injury are at higher risk of being injured again, possibly due to their running form (van Gent, et al., 2012). Davis, Bowser, & Mullineaux (2015) observed gait analysis parameters of 249 runners over two years, categorized by previously injured or never injured, and recorded how many people reported injuries. This allowed them to statistically quantify which of the recorded vertical loading variables were associated with specific injuries. They discovered that impact variables, such as magnitude of vertical impact peak and vertical loading rate, were all significantly higher in runners that sustained injuries (Davis, Bowser, & Mullineaux, 2015). Of the kinetic variables observed in previous studies, loading rate was consistently correlated with risk for overuse injury (Daoud, et al., 2012; Davis, Bowser, & Mullineaux, 2015; Hreljac, Marshall, & Hume, 2000; Radin & Paul, 1971; van Gent, et al., 2012). Increased loading rate was further supported as a risk for injury by Radin & Paul (1971) when they studied how joints responded to repetitive loading and found that bovine joint cartilage only showed significant wear after high loading rates. Therefore, loading rate is a key metric for determining reduction of risk for overuse injury.

Researchers examining the effect of minor alterations to running form on loading forces concur that loading rate is most dependent on foot strike pattern and therefore influences risk of injury (Daoud, et al., 2012; Giandolini, et al., 2012). Daoud et al. (2012) linked foot strike pattern and injury by observing 52 cross country runners over a nine-month period and recording reported injuries. They concluded that runners using a rear foot strike had significantly higher rates of repetitive stress injury compared to runners using a mostly forefoot strike. Giandolini, et al. (2012) did not study injury trends but observed impact variables after making acute interventions, such as wearing racing shoes, increasing step frequency, using a midfoot strike, and combing all three. Their results showed the most significant reduction in loading rate came from switching to a midfoot strike pattern and the combination. The results of both these studies could suggest that using a running form that reduces loading rate and uses a more forefoot strike pattern could be beneficial and reduce the risk for injury.

2.4 Good Form Running

After years of research, Good Form Running (GFR) was created in Michigan by Curt Munson and John Benedict in 2006 with a goal of giving people a better running experience by making them more efficient runners (Good Form Running with Striders, 2014). They wanted people to be able to run faster, farther, and avoid injuries (Good Form Running with Striders, 2014). The running style's popularity has led to it recently being adopted by New Balance® (Playmakers, 2016). GFR is characterized by a midfoot strike, high cadence, forward lean, and tall body alignment (Playmakers, 2016). Whereas common form is typically characterized by heel striking, over striding, and slower cadence (Playmakers, 2016; Nicola & Jewison, 2012). The difference in strike pattern at initial contact between common form running and GFR is illustrated in Figure 6 based on actual motion capture data.

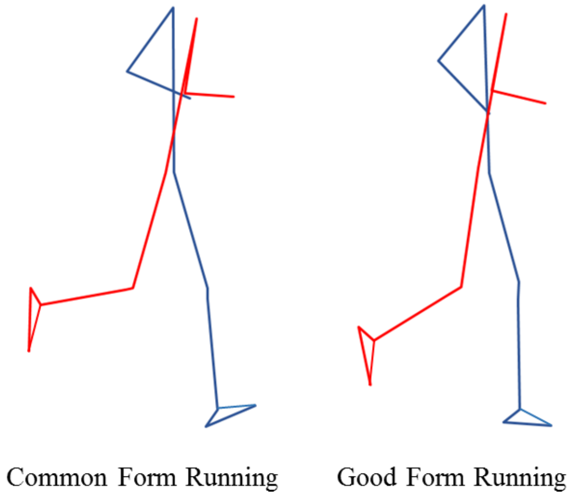

Figure 6: Sagittal Plane Comparison of Common Form Running to Good Form Running at Initial Contact

The foot, ankle, knee, hip, and upper body all play a role in maintaining the gait cycle and running efficiently (Nicola & Jewison, 2012). This is acknowledged in GFR by the close attention to posture described as an elongated spine, relaxed shoulders, and relaxed arms at a 90˚ angle (Playmakers, 2016). GFR also requires runners to lean forward from their ankles without bending at the waist to generate forward momentum (Playmakers, 2016). The midfoot strike for GFR is achieved by having the foot land under the hips with flexion in the knee to minimize braking at initial contact and provide more stability (Miller, 2016). A midfoot strike has been found by several other studies to reduce impact loading and therefore, risk of injury (Davis, Bowser, & Mullineaux, 2015; Lieberman, et al., 2010; Lieberman, Warrener, Wang, & Castillo, 2015; Giandolini, et al., 2012). Many of these studies have noted that the human body evolved running barefoot with a midfoot or forefoot strike pattern, so replicating this may help a runner achieve a more natural and efficient running form that takes advantage of lower limb anatomy (Daoud, et al., 2012; Davis, Bowser, & Mullineaux, 2015). Studies by Thompson, Lee, Seegmiller, & McGowan (2015), Cooper, Leissring, & Kernozek (2015), and De Wit, De Clercq, & Aerts (2000), conveyed that common form runners use a rearfoot strike pattern that has been made comfortable by thick cushioned running shoes but when asked to run barefoot almost everyone switched to a more forefoot strike pattern. To more easily accomplish the midfoot strike, GFR has a target cadence of 180 steps per minute, which is much quicker than what is used by common form runners (Playmakers, 2016). Increased cadence has also been associated with reduced loading on joints that may be beneficial in injury reduction (Heiderscheit, Chumanov, Michalski, Wille, & Ryan, 2011; Lieberman, Warrener, Wang, & Castillo, 2015).

Learning GFR requires gait retraining and practice over a month to ensure adaptation across all training speeds and reduce the risk of injury (Dugan & Bhat, 2005; Heiderscheit, 2011).

The progress of gait retraining is slow as to allow time for the body to become accustomed to the new muscular loading (Heiderscheit, 2011). Rear foot strikers use the muscles along the shin to dorsiflex the ankle at contact, while midfoot and forefoot strikers use the calf muscle to plantar flex the ankle (Nicola & Jewison, 2012). For most common form runners switching from a rear foot strike to a midfoot strike is challenging and can be painful if not done gradually (Heiderscheit, 2011). This knowledge helped in creating the training protocol for this study displayed in Appendix Figure A-1.

3 Description of Model

This study used a three-dimensional motion capture system and in-ground force plates to create a computational model of each runner. A marker set was used to calculate lower extremity sagittal plane segment and joint angles. The data from the in-ground force plates provided peak ground reaction forces during stance phase and was used to calculate loading rate.

3.1 Marker Set

For this study, a marker set was developed to observe sagittal plane kinematics of the left and right side at the same time. The sagittal plane in the lab was oriented in the y-z plane of the motion capture global coordinate system, with the y-axis from beginning of runway to end of runway and the z-axis from floor to ceiling. Markers were placed on bony prominences used to define segments in traditional two-dimensional biomechanics (Winter, 2009). Since a great majority of lower extremity motion occurs in the sagittal plane, as previously discussed in Section 2.1, and the marker set developed uses traditional biomechanics segment descriptions, the results of this study can be compared to other biomechanics studies without risk of incompatible segment definitions (Lieberman, Warrener, Wang, & Castillo, 2015; Thompson, Lee, Seegmiller, & McGowan, 2015). A total of 14 markers were used to make up a simple model of the lower extremities and trunk. Two markers were used for each segment to define the foot, shank, thigh, and trunk segments for the left and right side of the body. The markers were placed on the acromion, greater trochanter, lateral epicondyle of femur, head of fibula, lateral malleolus, 5th metatarsal head, and calcaneus on both sides of the body. The labels for these marker locations are shown in Table 1. The segment names and marker locations are illustrated in Figure 7. These markers were used to define segments and calculate joint angles. Since participants wore running shoes, the 5th metatarsal head and calcaneus markers were placed on shoes centered over the intended marker location. To compensate for the cushioned heel in most running shoes, the two foot markers were placed parallel to the ground. This ensured the foot and ankle angle would be accurately represented.

Table 1: Marker Set

Marker Name	Location
LSHL	Left Acromion
RSHL	Right Acromion
LHIP	Left Greater Trochanter
RHIP	Right Greater Trochanter
LFEM	Left Epicondyle of Femur
RFEM	Right Epicondyle of Femur
LFIB	Left Head of Fibula
RFIB	Right Head of Fibula
LANK	Left Lateral Malleolus
RANK	Right Lateral Malleolus
LHEE	Left Calcaneus
RHEE	Right Calcaneus
LTOE	Left 5th Metatarsal Head
RTOE	Right 5th Metatarsal Head

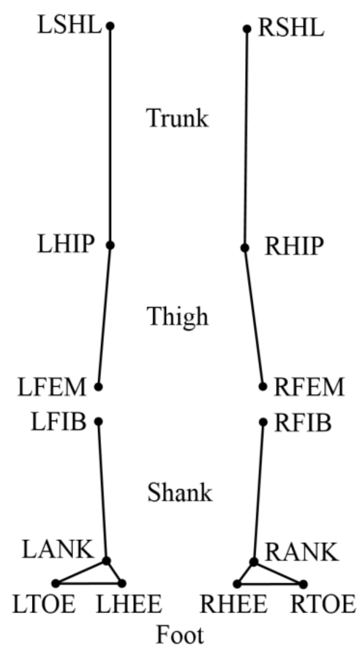

Figure 7: Marker Location and Segment Definition

3.2 Variable Calculations

Sagittal plane kinematics were calculated from the position data of each marker in the global reference frame of the motion capture volume. The parameters of focus in this study were hip angle, knee angle, ankle angle, vertical and fore-aft ground reaction forces, and loading rate of the vertical ground reaction forces. From these parameters, the variables used to quantify a difference in running form were joint angles at contact, peaks in ground reaction forces, and loading rate.

Segment angles are easily defined by marker locations for the lower extremity segments but not for the trunk. The trunk segment is traditionally defined as the greater trochanter to the glenohumeral joint (Winter, 2009). The glenohumeral joint is the shoulder socket joint and is represented by the acromion boney prominence located above the approximate joint center. Since the upper body rotates ina transverse plane about an inferior-superior axis while running, using the acromion and greater trochanter marker locations on either the left of the right side of the body would not accurately describe the sagittal plane trunk angle. To address this, the trunk angle at each point in time was obtained by taking the center point location between the left and right acromion and the left and right greater trochanter markers. The left and right acromion and left and right greater trochanter marker positions were averaged to make new marker names, TRNK and HIPS, using Equations 1-4.

$$TRNK_y = (RSHL_y - LSHL_y)/2 \quad \text{(Eq. 1)}$$

$$TRNK_z = (RSHL_z - LSHL_z)/2 \quad \text{(Eq. 2)}$$

$$HIPS_y = (RHIP_y - LHIP_y)/2 \quad \text{(Eq. 3)}$$

$$HIPS_z = (RHIP_z - LHIP_z)/2 \quad \text{(Eq. 4)}$$

Segment angles are given below in Equations 5 - 8 using right side marker names given in Figure 7. Joint angles are calculated using segment angles and Equations 9 - 11. A visual representation of the joint angles is given in Figure 8. The hip angle is the femur relative to the trunk. It is 0˚ when the femur is in line with the trunk, negative when extended, and positive when flexed. The knee angle is the difference between the femur and tibia. It is 0˚ when the leg is fully extended and only moves in the positive direction when running. The knee flexion/extension is determined by the increasing or decreasing of the angle, flexion when increasing and extension when decreasing. The ankle angle is the foot relative to the tibia with 90˚, or neutral, plotted at 0˚. The ankle is dorsiflexed when the angle is positive and plantarflexed when the angle is negative.

$$Trunk\ Angle = \arctan\left(\frac{TRNK_z - HIPS_z}{TRNK_y - HIPS_y}\right) \quad \text{(Eq. 5)}$$

$$Thigh\ Angle = \arctan\left(\frac{RHIP_z - RFEM_z}{RHIP_y - RFEM_y}\right) \quad \text{(Eq. 6)}$$

$$Shank\ Angle = \arctan\left(\frac{RFIB_z - RANK_z}{RFIB_y - RANK_y}\right) \quad \text{(Eq. 7)}$$

$$Foot\ Angle = \arctan\left(\frac{RHEE_z - RTOE_z}{RHEE_y - RTOE_y}\right) \quad \text{(Eq. 8)}$$

$$Hip\ Angle = Thigh\ Angle - Trunk\ Angle \quad \text{(Eq. 9)}$$

$$Knee\ Angle = Thigh\ Angle - Shank\ Angle \quad \text{(Eq. 10)}$$

$$Ankle\ Angle = Foot\ Angle - Shank\ Angle - 90^{\circ} \quad \text{(Eq. 11)}$$

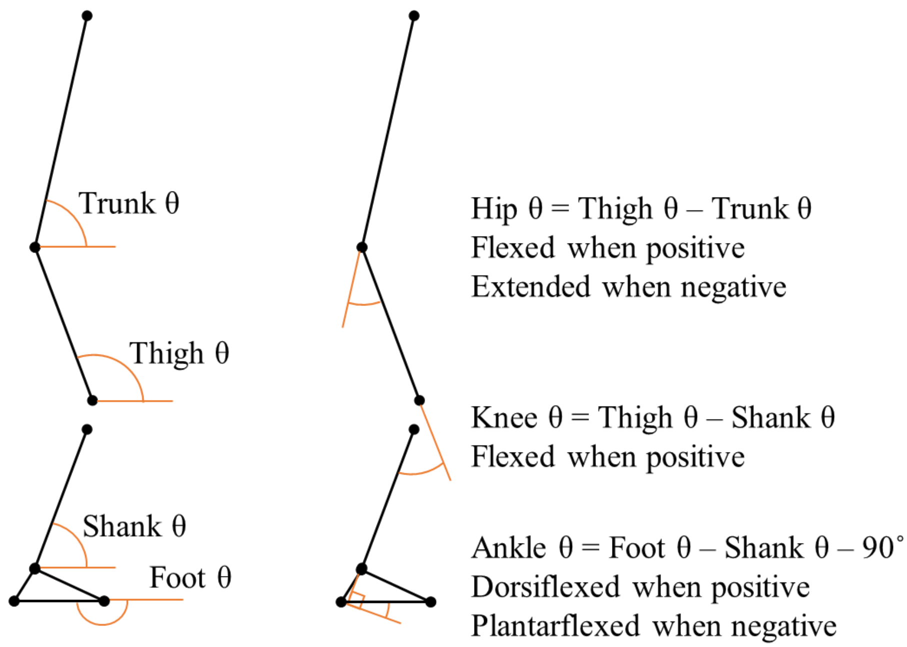

Figure 8: Visual Explanation of Segment and Joint Angles

The kinetic variables of interest in this study were loading rate, maximum vertical ground reaction force, maximum horizontal ground reaction force, and minimum horizontal ground reaction force. Loading rate is the only kinetic variable that needed to be calculated since the other variables were pulled directly from force plate data. The loading rate was calculated using Equation 12 where the force and time at 20 and 80 percent of the first or only peak were used to calculate slope, as previously explained in Section 2.1. For this equation, the unit for force was multiple of body weight (BW) and the unit for time was seconds (s), making the units for loading rate body weight per second (BW/s).

$$Loading\ Rate\ = \frac{(Force80 - Force20)}{(Time80 - Time20)} \quad \text{(Eq. 12)}$$

As previously discussed in Section 2.1, the ground reaction forces being observed in this study are in some way dependent on running velocity, making speed an important parameter to monitor. The speed was calculated from motion capture data. The distance between the position of the calcaneus marker on the planted foot at the beginning and end of a gait cycle was divided by the time it took to complete one gait cycle as shown using right side marker names in Equations 13 – 15. In these equations, *n* is the number of frames for one gait cycle and f_s is the motion capture sampling rate.

$$Gait\ Distance = RHEE_y(n) - RHEE_y(1) \quad \text{(Eq. 13)}$$

$$Gait\ Time = \frac{n}{f_s} \quad \text{(Eq. 14)}$$

$$Trial\ Speed = \frac{Gait\ Distance}{Gait\ Time} \quad \text{(Eq. 15)}$$

4 Experimental Design

This longitudinal pilot study was designed to compare common form running to Good Form Running. Sagittal plane lower extremity kinematics and ground reaction forces were observed at three conditions; before gait retraining, after gait retraining, and one month after gait retraining. Data was collected using a three-dimensional motion capture system with 8 cameras, 14 reflective markers, and 3 in-ground force plates. Statistical differences in key variables between conditions were determined using statistical software.

4.1 Participant Selection

A challenge for this study and other longitudinal studies was the difficulty in finding participants willing to commit to follow up data collections and, for this study specifically, the month-long training. Twelve healthy runners, 6 males and 6 females, 18-50 years old (mean ± standard deviation: mass 67.8 ± 8.7 kg, height 172.7 ± 8.4 cm) were recruited from various running groups in the Grand Rapids area and students from Grand Valley State University. Interested runner's acceptance was based on their ability to meet the following requirements.

1) Healthy adult between 18 and 50 years of age (the maximum age of 50 was chosen because persons under this age are less likely to have gait altering injuries or ailments).
2) Run regularly, preferably 10 miles a week, and run with a rear foot strike.
3) Have had no minor lower extremity injuries within 6 months prior to study and not experiencing any pain or lingering symptoms from these injuries (e.g. sprained ankle).
4) Have never had a major lower extremity injury (e.g. anterior cruciate ligament injury).
5) Did not have a significant medical condition like a neurological disease that impairs movement (e.g. multiple sclerosis), uncontrolled high blood pressure, unstable heart disease, or respiratory disease.

Prior to participation participants read and signed informed consent and provided brief medical history. Demographic information gathered was used to characterize the sample. The Human Research Review Committee at Grand Valley State University approved this study, reference file number 16-187-H. For statistical analysis, the sample population used for this study is assumed to be a simple random sample from a population of similar participants.

4.2 Equipment

Marker trajectories were acquired using an optoelectric system with 8 MX-T40 cameras collecting data at 120 Hz, a set of 14 mm reflective markers, and Nexus 2.5 motion capture software (Vicon Motion Systems Ltd., Los Angeles, CA). The MTX-T40 cameras had a 4-megapixel resolution and used a near infrared high power strobe to track reflective markers. After calibration, the accuracy of marker location, image error, was within 0.2 and 0.3 mm. Ground reaction forces of all running trials were determined by using one of three in-ground force plates collecting data at 1200 Hz with an accuracy of ±0.1% of applied load (Advanced Mechanical Technology Inc., Watertown, MA). The literature suggests that within and between day repeatability for sagittal plane kinematic variables and ground reaction forces are sufficient and better than transverse and coronal plane variables (Kadaba, et al., 1989). Repeatability was also determined to not be affected by participants running at a self-selected pace versus at a standardized pace (Queen, Gross, & Liu, 2006). All data collections were conducted in the Biomechanics and Motor Performance Lab (BMPL) at Grand Valley Statue University. The lab was approximately 12.2 m x 16.8 m and the capture volume for participants to run through covered a ground area of 1.8 m x 7.3 m.

4.3 Procedure

Data was collected on each participant three times over two sessions to observe three conditions, before training, after training, and one month after training. In each session, reflective markers were taped to participant's shoes and body using hypoallergenic tape. An experienced physical therapist aided in anatomical placement of reflective markers. Markers were placed in locations previously discussed in Section 3.1. To maximize marker identification and reduce motion artifact participants wore form-fitting shorts and were given the options of wearing a tank top or being shirtless (girls wearing a sports bra). Before each data collection runners warmed up on a treadmill and practiced running through the lab and motion capture space until they felt comfortable. Data was collected at each runner's selected training pace and in the runner's personal shoes. Three successful running trials were collected for each foot for all three conditions, amounting to 18 running trials per participant. A successful running trial was characterized by a clean foot strike landing in the center of one of the three force platforms, embedded flush with the floor in the capture volume, and all markers visible for one full gait cycle.

In the first session, all participant questions were answered, consent forms were signed, medical screenings were filled out, and the first two conditions (i.e. before and after gait retraining) of running data were collected. The first session data collection started with a static trial, for which the participants stood still on one force plate to record body weight for normalization purposes. Next the participants ran with common form at their preferred training pace. The data collected pre-training were characterized as common form running. After the common form data collection, the participants were trained in Good Form Running by an experienced coach. This training involved an explanation and background of Good Form Running, step by step instructions on how to hold the body while running, and the proper foot strike. Participants then ran at a cadence of

180 strides per minute with the aid of a metronome. Running data was collected again once the coach had verified that the participant had successfully demonstrated the new running form.

In between the two data collection sessions, participants followed a month-long training sheet given in Appendix Figure A-1 that helped get them accustomed to the new running form (Dugan & Bhat, 2005; Heiderscheit, 2011). The training program was explained in detail by the coach before participants left the first data collection session. The first half of training involved only jogging in place using the proper foot strike and posture to get the runners used to the new muscular loading and prevent injury (Dugan & Bhat, 2005). In the second half of training, the participants started jogging and gradually picking up speed till they reached their normal running pace. Participants also met with the coach at the BMPL to practice Good Form Running two weeks after their first session. This in-between training with the GFR coach was used to make sure participants were practicing the new form properly and adhering to the training program presented.

The second session of data collection was approximately one month after the first session, when the participants had been given ample time to become accustomed to the new running form. The coach was present to check the runners form one more time before the last data collection. In this data collection, another static trial was collected, followed by 6 more trials (3 for each side of the body) of the participant using Good Form Running.

5 Data Analysis

To more easily observe and analyze running form, each running trial recorded in the motion capture system was trimmed to one gait cycle, starting a frame before foot strike on a force plate and ending with the subsequent initial contact of the same foot. This subsequent initial contact was identified by when the calcaneus marker of interest was once again closest to the ground. Marker data collected for each trial was labeled and gaps in marker trajectories were filled using two different interpolation methods in Nexus 2.5 (Vicon Motion Systems Ltd., Los Angeles, CA). Small gaps in marker trajectory data were either spline filled or pattern filled. Spline gap fill used a Woltring quintic spline function for gaps of less than 10 frames (Woltring, 1985). A pattern gap fill used the trajectory of a marker with similar motion for gaps larger than 10 frames. The marker trajectory and force plate data were then exported from Nexus 2.5 in a comma separated values file (.csv). Gaps in data were observed during data collection and trials were thrown out and redone if critical marker gaps were too large (over 20 consecutive frames).

The exported data for each running trial was processed and analyzed using functions written in MATLAB® (MATLAB 6.1, The MathWorks Inc., Natick, MA, 2000). All data was filtered using a 4^{th} order two-way low pass Butterworth filter to reduce signal noise. This filter is typically used for motion capture analysis because it filters out the high frequency noise accompanying movement without modifying the lower frequency signal and does not phase shift the data (Bruce, 2000). Motion capture data was filtered with a cut off frequency of 15 Hz, horizontal ground reaction force data was filtered at 25 Hz, and vertical force plate data was filtered at 100 Hz. These cut off frequencies were selected based on previous works and examination of at what cut off frequency reduced the most noise without distorting the signal (Hunter, Marshall, & McNair, 2005; Noehren, Davis, & Hamill, 2007). The marker trajectories from motion capture were used to calculate kinematic parameters such as hip angle, knee angle, ankle angle, and trial speed with equations given in section 3.2. Force plate data were used to calculate and extract the loading rate, maximum vertical ground reaction force, maximum fore-aft ground reaction force, and minimum fore-aft ground reaction force for each trial. Joint angles and ground reaction forces were normalized from 0 - 100% gait cycle for easier comparison among trials. Ground reaction forces were also normalized by participant body weight. All of the data filtering and variable calculations were executed using code written specifically for this study in MATLAB®.

For each condition (before training, after training, and one month after training), key variables were compared for significant differences using repeated measures ANOVA (analysis of variance) in JMP Pro 13 (SAS Institute, Cary, NC, USA). Since there were three trials for each foot per condition, the kinematic and kinetic variables for the three trials were averaged, giving left and right variables for each participant for all three conditions. The values at ground contact for each of the joint angles, the peak values for ground reaction forces, and loading rate for each condition were compared for statistical significance. The percent difference of the mean between common form running and Good Form Running was also calculated for each variable.

Repeated measures ANOVA is used when observing the response of an intervention, on the same participant, over time (Daniel & Cross, 2013). Since every participant has a unique running background and anatomy, comparing their responses to the same training over a month could lead to large variability and error (Montgomery, 2013). This increase in error would make it more difficult to detect difference between conditions (Montgomery, 2013). Repeated measures ANOVA controls for variation among participants and tests for differences between related dependent variables (Daniel & Cross, 2013). This statistical analysis was used to find the significant differences of all variables before gait retraining, after gait retraining, and one month after. Variables were considered statistically significant if they rejected the null hypothesis that there was no difference between the three conditions. The P-value, or calculated probability of finding the null hypothesis to be true, was set at 0.05 (Daniel & Cross, 2013). Therefore, if the repeated measures ANOVA returned a P-value less than 0.05 ($p < 0.05$), the parameter being tested was determined to be statistically significant and post-hoc analysis was required for further conclusions to be reached (Daniel & Cross, 2013). Similarly, for the conclusion of the repeated measures ANOVA to be validated, data for each variable was required to be from a normally distributed population and not violate sphericity (Daniel & Cross, 2013).

Normality of each variable was established by examining residuals normal quantile plots, where data is plotted as the difference between actual value and predicted value. Variables were considered to be samples from a normal distribution if all points remained inside the 95% confidence interval. Sphericity is defined as the variance of differences between all combinations of conditions being equal (Daniel & Cross, 2013). The assumption of sphericity was verified using a Mauchly's sphericity test. If the test came back significant ($p < 0.05$), sphericity was rejected and further corrections were necessary to obtain accurate results from repeated measures ANOVA (Daniel & Cross, 2013).

The matched pairs post-hoc analysis was used to establish which paired combination of the three conditions were statistically significant for each variable, using the same P-value as before and testing the null hypothesis that there was no difference between conditions. Using multivariate analysis, correlations between variables, including trial speed, were also explored for a more complete understanding of the gait retraining and running forms. Correlation is the ability of one variable to predict the value of another variable using a linear function. Correlation values range from 0 to 1, with 1 being perfectly correlated, and were considered meaningful for this study if they were greater than 0.7 ($r > 0.7$). Multivariate analysis was performed between all variables over all conditions, as well as between variables within common form running, condition 1, and Good Form Running, condition 3, specifically. While the purpose of this study was to quantify statistical difference between common form running, condition 1, and Good Form Running, condition 3, statistical analysis was executed for variables between all conditions. This extra analysis gave insight to the effectiveness of the gait retraining process for Good Form Running.

6 Results

Sagittal plane lower extremity kinematics, vertical and fore-aft ground reaction forces, and loading rate were observed for 12 runners: before gait retraining (condition 1), after gait retraining (condition 2), and one month after gait retraining (condition 3). Left and right side joint angles and ground reaction force graphs were generated for each participant and can be seen in the Appendix Figure A-2 to Figure A-25. These graphs show the average of the three trials collected for the specific side of the body for each condition. In these graphs, the solid line is before gait retraining, the dotted line is after gait retraining, and the dashed line is one month after gait retraining. All graphs display one gait cycle, beginning and ending with initial contact. The variables extracted from this were loading rate, maximum vertical GRF, maximum fore-aft GRF, minimum fore-aft GRF, hip angle at contact, knee angle at contact, and ankle angle at contact. These variables were analyzed to quantify a difference between common form running and Good Form Running. An abridged spreadsheet, with each participants' variables averaged for left and right side of the body, is shown in Table A-1. Trial speed was added to this table and the multivariate analysis to find which variables were correlated and dependent on speed. The table of correlations based on condition and between all conditions can be seen in Appendix Table A-2.

A repeated measures ANOVA was executed, for all three conditions, on every variable (hip, knee, and ankle angles at contact, peak GRF's, and loading rate) and each one was deemed significant ($p < 0.05$), meaning significant differences occurred between conditions. Since none of the variables violated the assumption of sphericity and residuals analysis showed they were all adequately normal, the repeated measures conclusions were valid. Statistical analysis revealed an overall significant difference for all variables between conditions 1 and 2, before training and right after training. Loading rate, minimum fore-aft GRF, knee angle at contact, and ankle angle at contact were also significantly different between condition 1 and 3, before training and one month after training. These are the variables determined to be significant between common form running and Good Form Running. Maximum vertical GRF, maximum fore-aft GRF, hip angle at contact, knee angle at contact, and ankle angle at contact were all significantly different between conditions 2 and 3, after training and one month after training. Only knee angle at contact and ankle angle at contact were significant between all conditions. P values for all variable at every combination of conditions are given in Table A- 3, with highlighted values indicating significance ($p < 0.05$).

To display the data collected and illustrate difference between conditions, the mean of critical variables and trial speed for all participants have been graphed to show the overall change between conditions 1, 2, and 3. The mean graphs do not control for variation among participants like the repeated measures ANOVA. The graphs for mean loading rate (Figure 9), maximum vertical ground reaction force (GRF) (Figure 11), maximum horizontal GRF (Figure 13), minimum horizontal GRF (Figure 14), hip angle at contact (Figure 16), knee angle at contact (Figure 18), ankle angle at contact (Figure 20), and trial speed (Figure 22) are shown with individual data points plotted as well. Mean values in the text are followed by ± 1 standard deviation. Individual comparison for each key variable between condition 1, common form running, and condition 3, Good Form Running are also shown using bar charts (Figure 10Figure 12, Figure 15Figure 17Figure 19Figure 21Figure 23).

Loading rate was significantly different between conditions 1 and 2 ($p < 0.0001$) and conditions 1 and 3 ($p < 0.0001$). Figure 9 shows that mean loading rate dropped significantly after gait retraining and was maintained at the one month follow up. The loading rate mean started off at 56.1 ± 11.6 BW/s, then reduced to 30.2 ± 9.5 BW/s after gait training, and was ultimately cut in half after one month of training to be 27.9 ± 7.2 BW/s. There was a 50.3% decrease in mean loading rate between conditions 1 and 3. A direct comparison of participant loading rate between common form running and Good Form Running is shown in Figure 10. The multivariate analysis between all conditions showed a correlation for loading rate and ankle angle (r = 0.720). Multivariate analysis based on condition revealed a correlation between loading rate and maximum vertical GRF for condition 1 (r = 0.719) and condition 3 (r = 0.748).

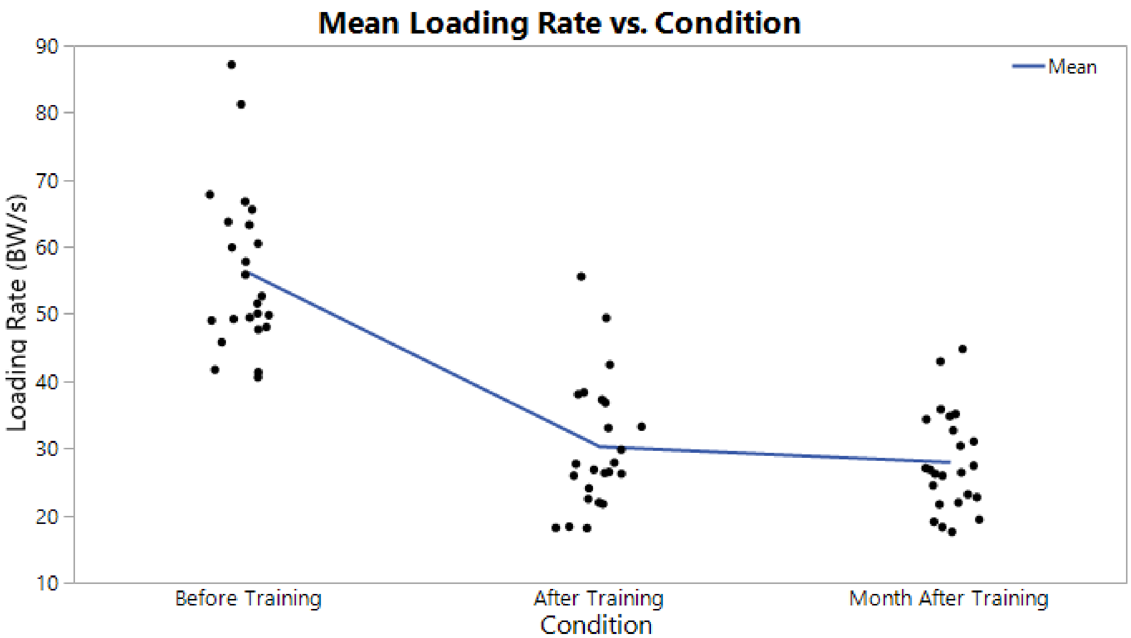

Figure 9: Mean Loading Rate vs. Condition

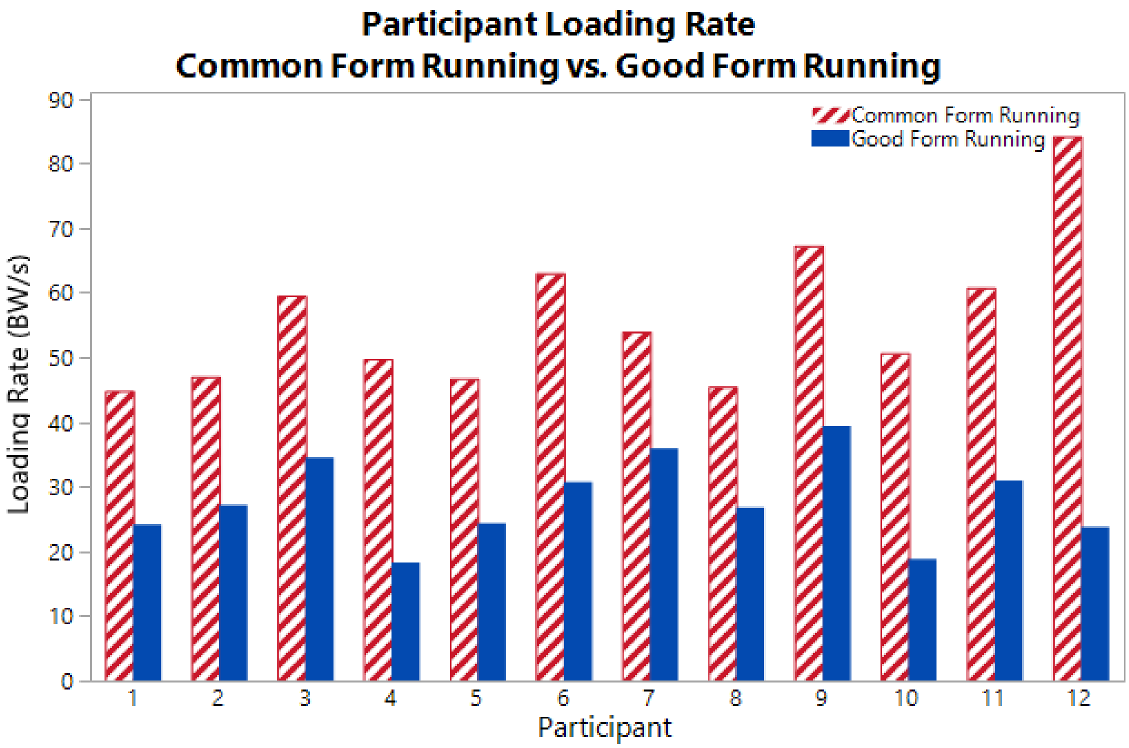

Figure 10: Participant Loading Rate for Common Form Running vs Good Form Running

Maximum vertical GRF was significant between conditions 1 and 2 (p = 0.0034) and conditions 2 and 3 (p = 0.0095). Mean maximum vertical GRF is graphed in Figure 11 and shows the mean decreased from 2.43 ± 0.17 BW to 2.31 ± 0.25 BW after training but came back up to 2.38 ± 0.25 BW after the one month of training. There was only a 2.1% decrease in mean maximum vertical GRF between common form running and Good Form Running. The difference in peak vertical GRF between the two forms is shown in Figure 12 for each participant. The maximum vertical GRF was considered correlated with maximum fore-aft GRF (r = 0.710) and trial speed (r = 0.723) between all conditions. The multivariate analysis based on condition determined maximum vertical GRF to be correlated with loading rate (r = 0.719) before training, with maximum horizontal GRF (r = 0.733) and trial speed (r = 0.765) right after training, and with loading rate (r = 0.748), maximum fore-aft GRF (r = 0.774), and trial speed (r = 0.786) after one month of training.

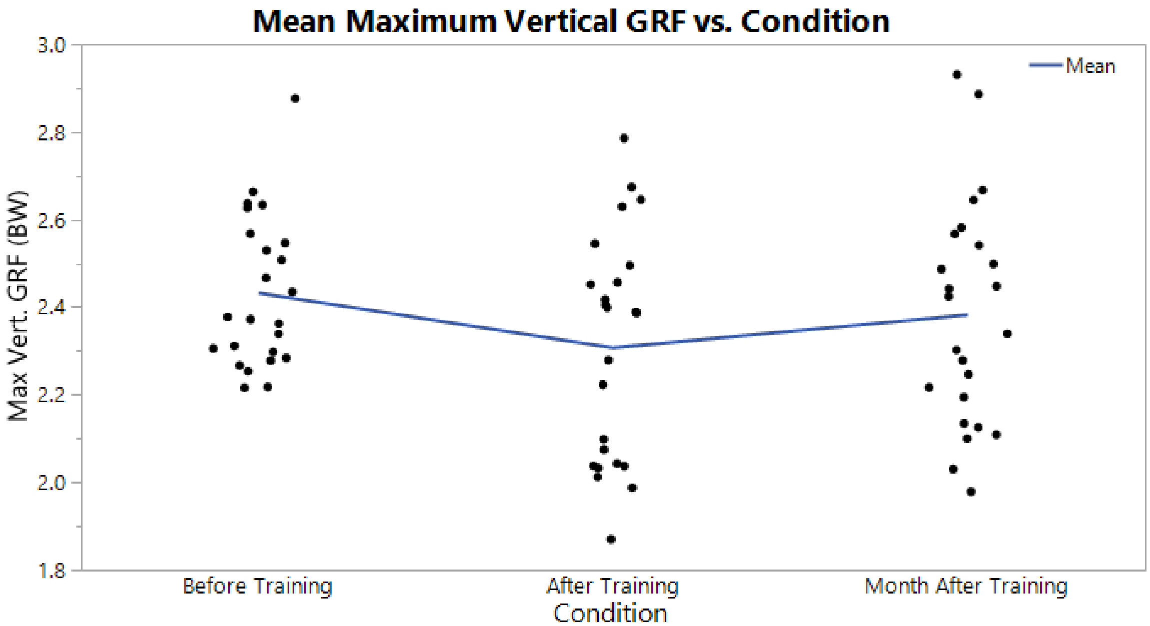

Figure 11: Mean Maximum Vertical Ground Reaction Force vs. Condition

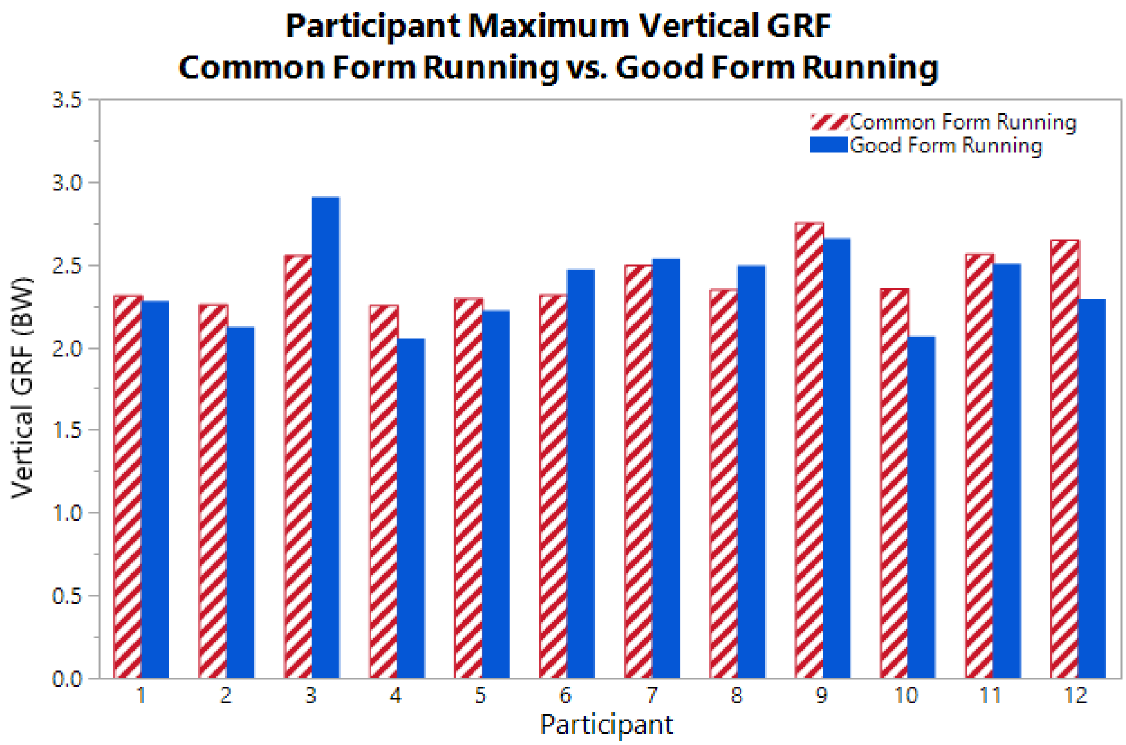

Figure 12: Participant Maximum Vertical GRF for Common Form Running vs. Good Form Running

Maximum fore-aft/horizontal GRF is the maximum propulsion force and was significant between conditions 1 and 2 ($p = 0.0029$) and conditions 2 and 3 ($p = .0003$). The mean minimum horizontal GRF is the braking force and was significant between conditions 1 and 2 ($p < 0.0001$) and conditions 1 and 3 ($p < 0.0001$). This means minimum horizontal GRF is significant between common form running and Good Form Running but maximum horizontal GRF is not. Figure 13 displays that mean maximum propulsion force dropped after training, from 0.246 ± 0.045 BW to 0.207 ± 0.056 BW, but came back up after one month of training to 0.247 ± 0.067 BW, almost the same as the first condition but with greater variance. Figure 14 shows that mean peak braking force decreased from -0.304 ± 0.037 BW to -0.225 ± 0.060 BW between conditions 1 and 2, but increased slightly for the third condition to -0.238 ± 0.064 BW. This presents a 0.6% increase in mean maximum horizontal GRF and a 21.6% decrease in mean minimum horizontal GRF. Maximum and minimum horizontal GRF for each participant with common form running and Good Form Running is shown in Figure 15. Where the positive bars are maximum horizontal GRF and the negative bars are minimum horizontal GRF. The maximum horizontal GRF was deemed correlated with maximum vertical GRF ($r = 0.710$) and trial speed ($r = 0.833$) over all conditions. Before training maximum horizontal GRF was correlated with trial speed ($r = 0.745$). Right after training it was correlated with maximum vertical GRF ($r = 0.733$), minimum horizontal GRF ($r = -0.736$), and trial speed ($r = 0.882$). One month after training it was correlated with maximum vertical GRF ($r = 0.774$) and trial speed ($r = 0.876$). Minimum horizontal GRF was considered significantly correlated to trial speed over all conditions ($r = 0.785$) and was correlated with maximum horizontal GRF ($r = -0.736$) and trial speed ($r = -0.858$) at condition 2.

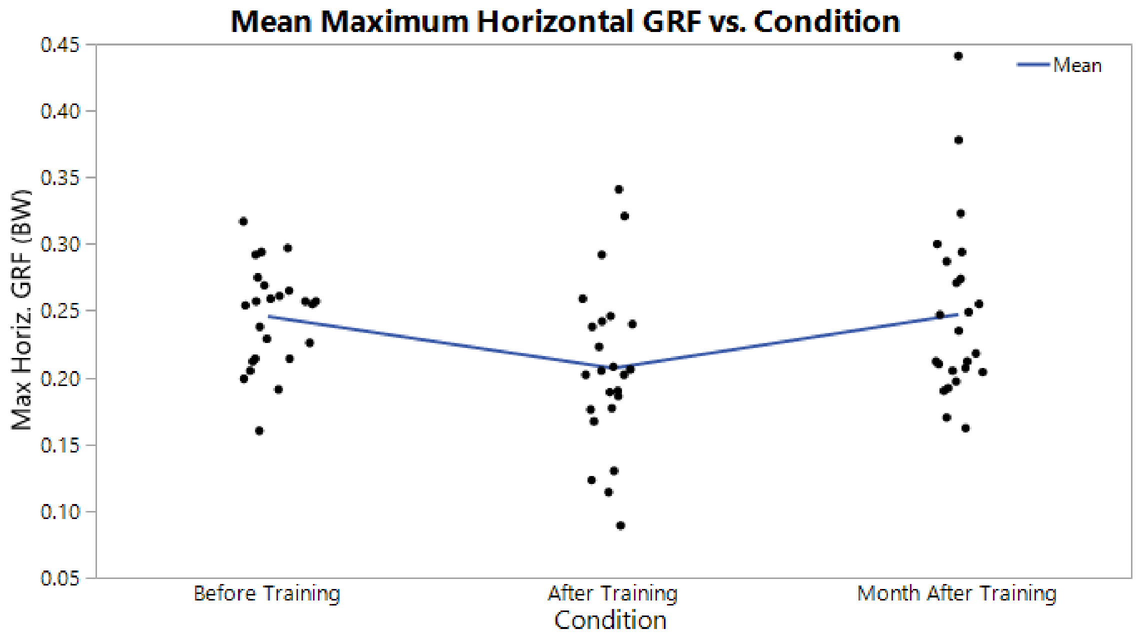

Figure 13: Mean Maximum Horizontal Ground Reaction Force vs. Condition

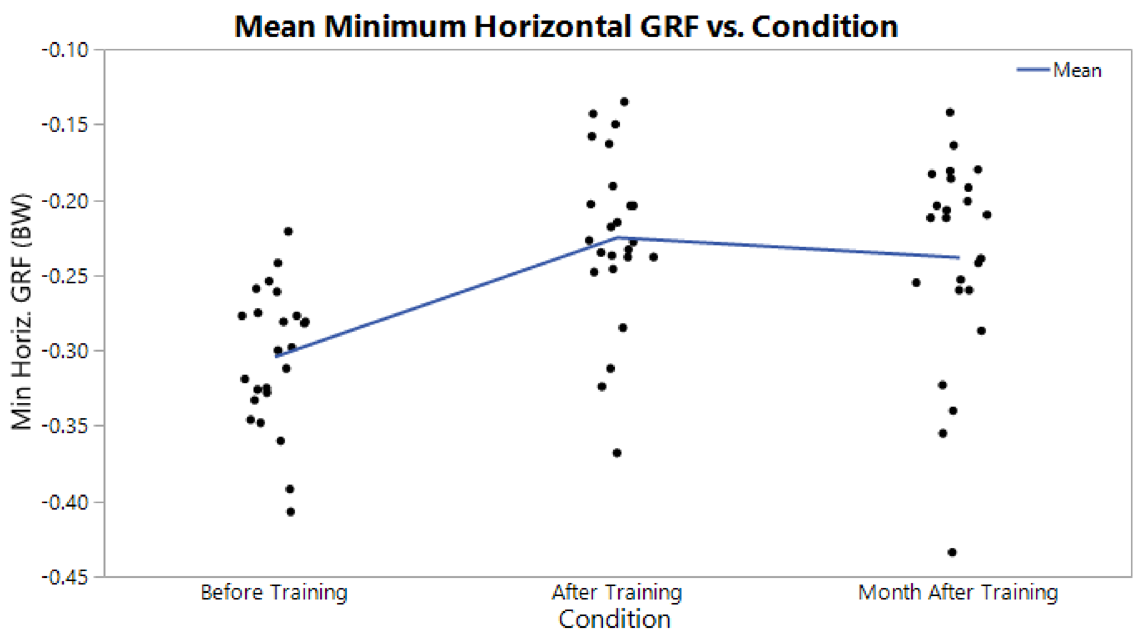

Figure 14: Mean Minimum Horizontal Ground Reaction Force vs. Condition

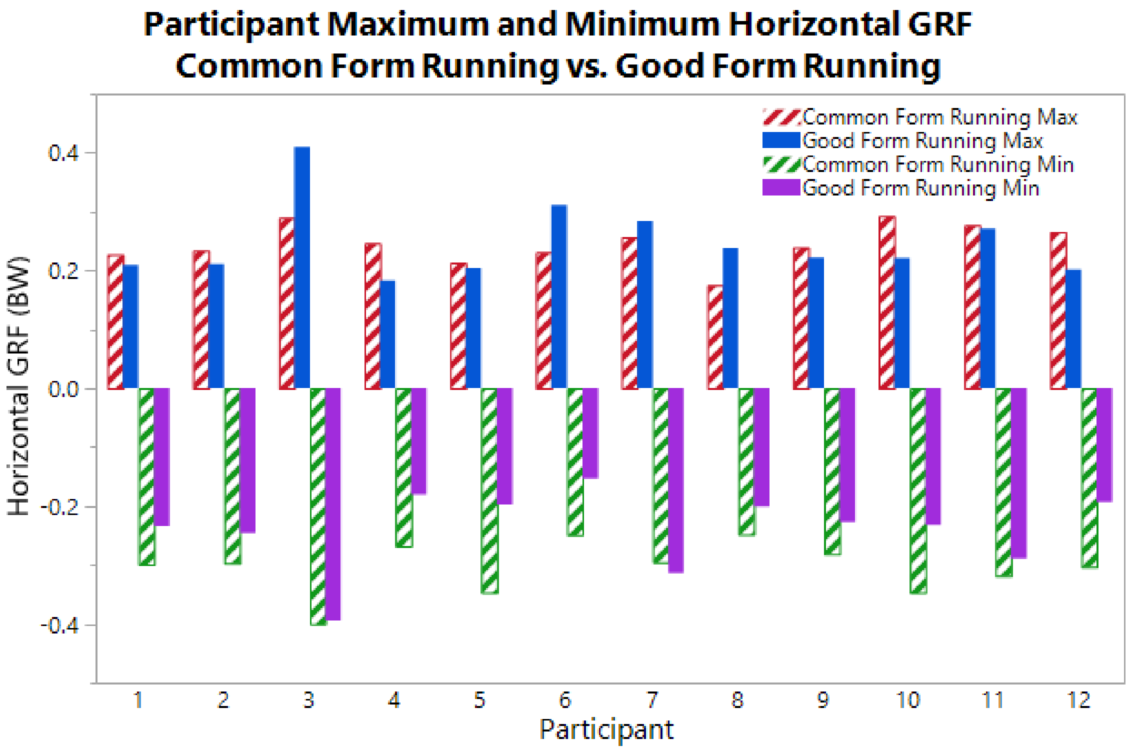

Figure 15: Participant Maximum and Minimum Horizontal GRF for Common Form Running vs. Good Form Running

The hip angle at contact was statistically significantly different between conditions 1 and 2 ($p < 0.0001$) and conditions 2 and 3 ($p < 0.0002$). The mean hip angle at contact is plotted in Figure 16 and displays a decrease from before training to after training, from 27.0 ± 5.5˚ to 23.6 ± 5.3˚, and an increase back to 26.4 ± 5.2˚ after one month of training. With very little difference in mean between condition 1 and 3, there was only a 2.4% decrease in hip angle at contact between common form running and Good Form Running. The hip angle at contact for common form running and Good Form Running of each runner is compared in Figure 17. Multivariate analysis concluded that hip angle at contact was not significantly correlated with any other variable over all conditions but was significantly correlated with knee angle ($r = 0.701$) during Good Form Running.

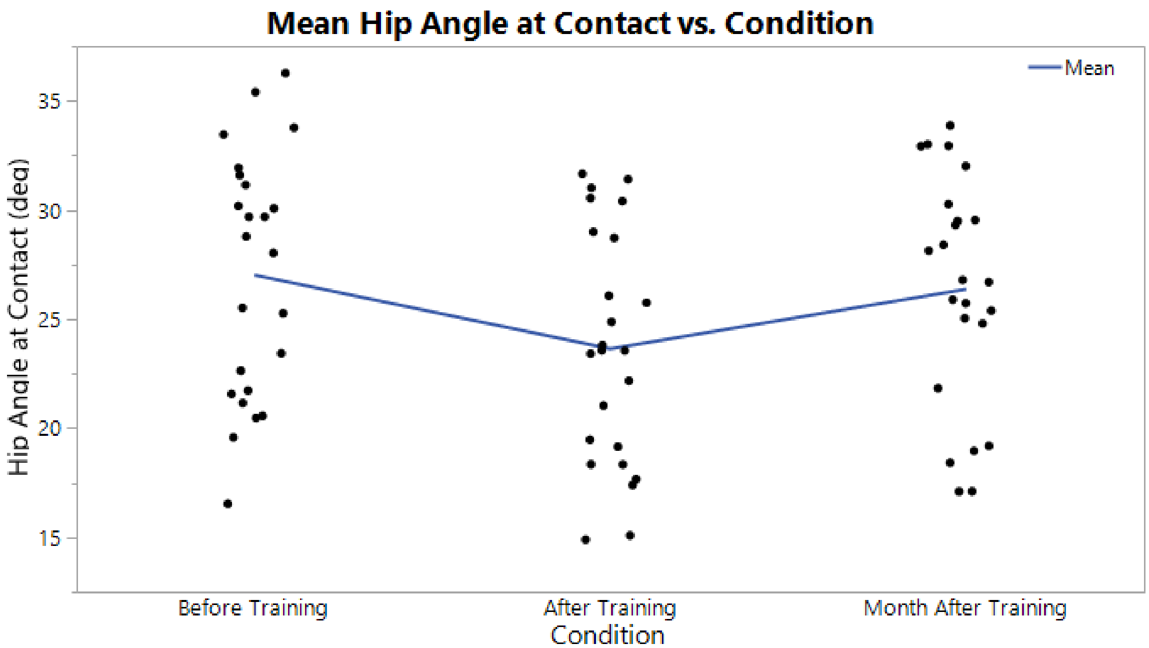

Figure 16: Mean Hip Angle at Contact vs. Condition

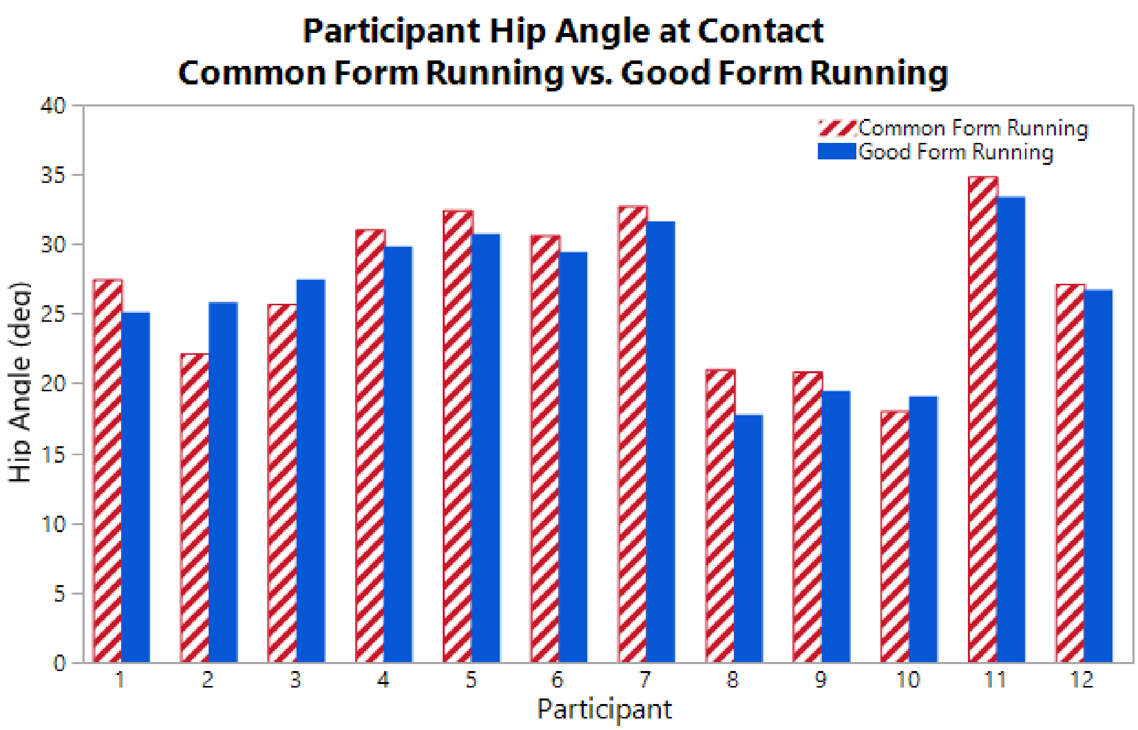

Figure 17: Participant Hip Angle at Contact for Common Form Running vs. Good Form Running

Knee angle at contact was statistically significantly different between all combinations of conditions ($p_{1-2} < 0.0001$, $p_{1-3} < 0.0001$, $p_{2-3} < 0.0033$). The mean knee angle at contact depicted in Figure 18, increases linearly from condition 1 to condition 3. The mean knee angle is initially 17.3 ± 2.5˚ for common form running, then increases to 19.9 ± 2.9˚ after gait retraining, and continues to increase to 22.5 ± 3.9˚ after one month of training. The mean knee angle increases by 29.5% between condition 1 and condition 3. The knee angle at contact for these conditions is displayed in Figure 19 to compare common form running and good form running for each participant. Multivariate analysis specified that knee angle at contact was not significantly correlated to any variable over all conditions but was correlated to hip angle in condition 3 (r = 0.701).

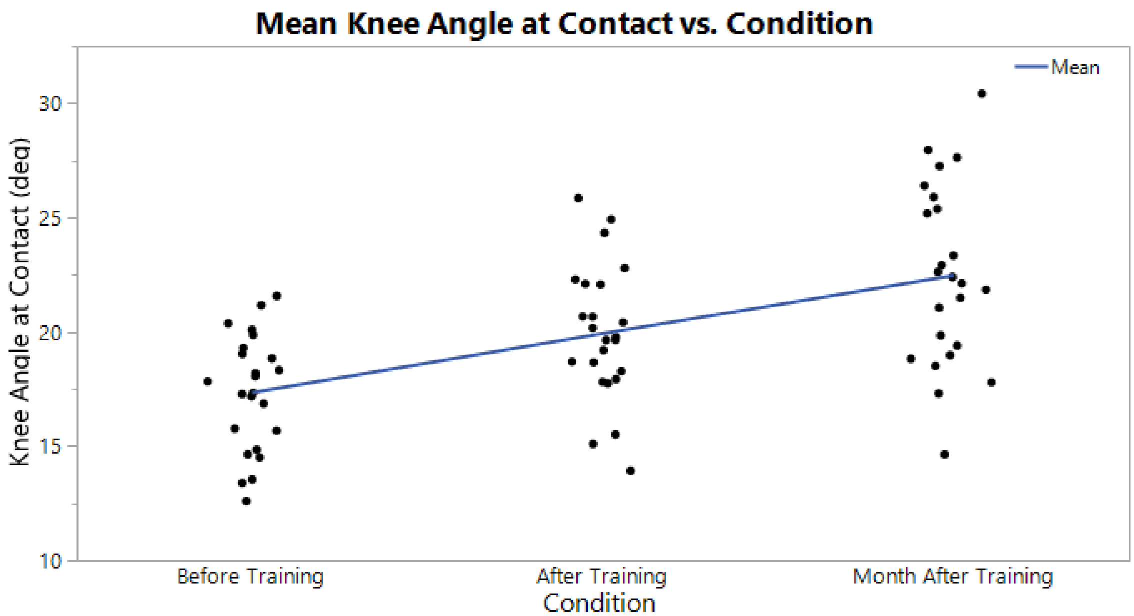

Figure 18: Mean Knee Angle at Contact vs. Condition

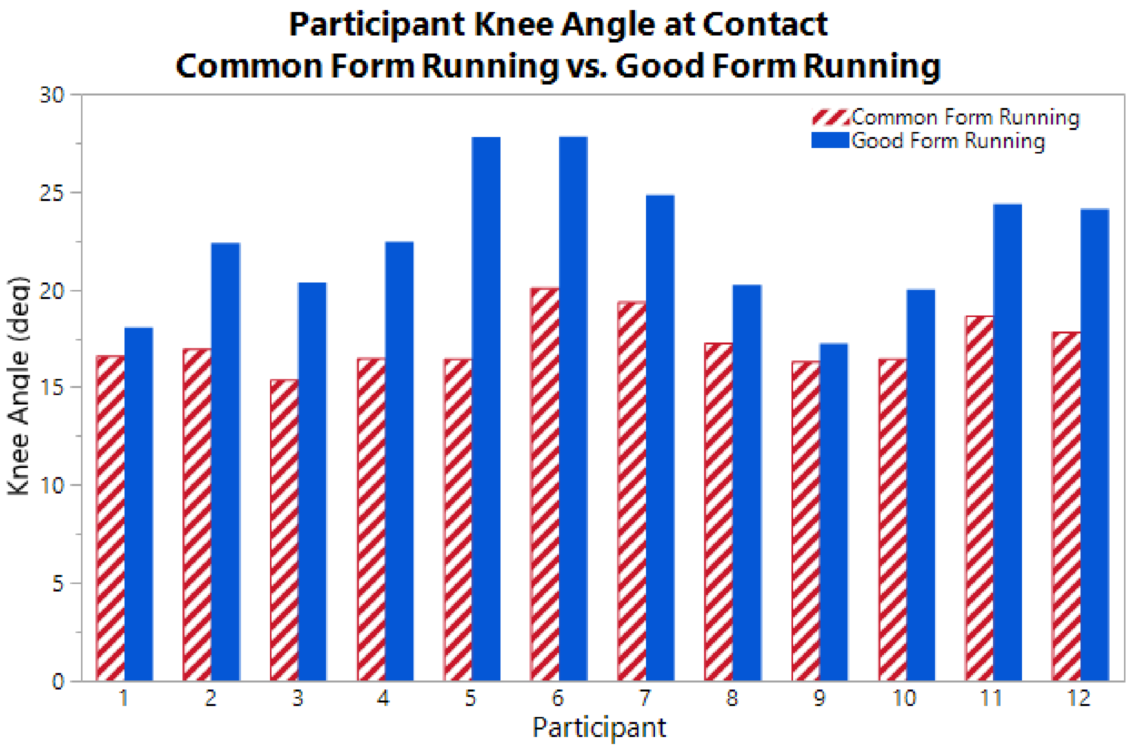

Figure 19: Participant Knee Angle at Contact for Common Form Running vs. Good Form Running

Ankle angle at contact was also statistically significantly different between all combinations of conditions ($p_{1\text{-}2} < 0.0001$, $p_{1\text{-}3} < 0.0001$, $p_{2\text{-}3} < 0.0128$). The mean ankle angle in Figure 20 decreases significantly at every condition, going from positive values signifying ankle dorsiflexion, 7.61 ± 3.0˚ before training, to negative values signifying ankle plantarflexion, -1.96 ± 5.9˚ after training and -5.36 ± 3.5˚ after one month of training. The mean ankle angle demonstrated the greatest percent difference between condition 1 and condition 3 with a 170% decrease. The ankle angle for every participant before training and one month after training is exhibited in Figure 20. This bar chart shows that every participant ran with a positive ankle angle with common form and every participant switched to a negative ankle angle with Good Form Running, except participant 2. The ankle angle at contact was only found to be significantly correlated to loading rate overall conditions (r = 0.720).

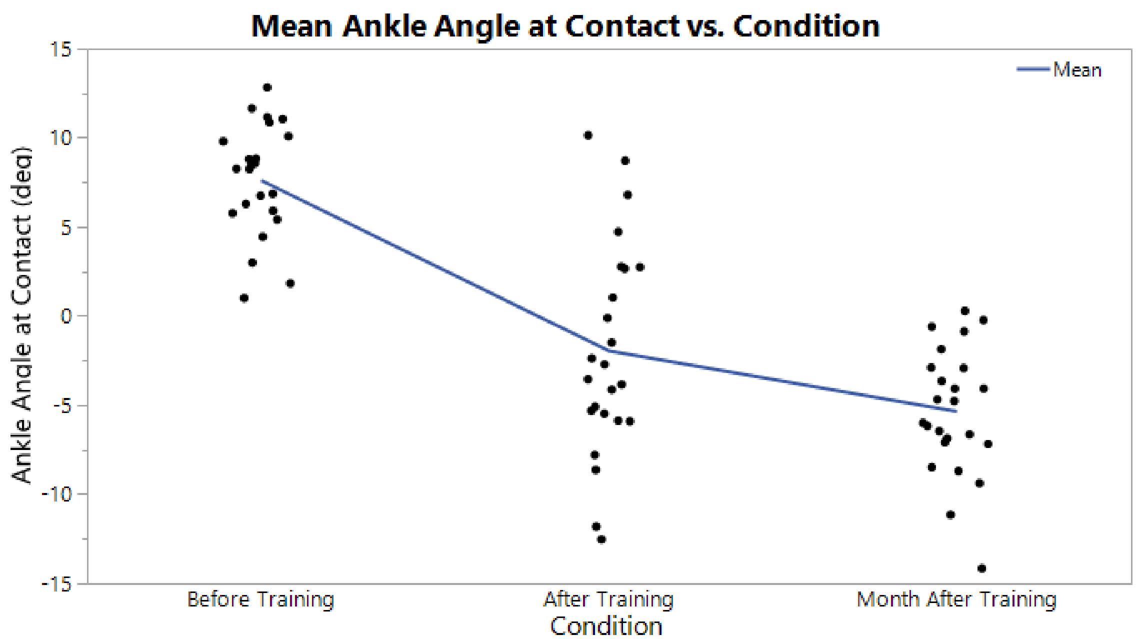

Figure 20: Mean Ankle Angle at Contact vs. Condition

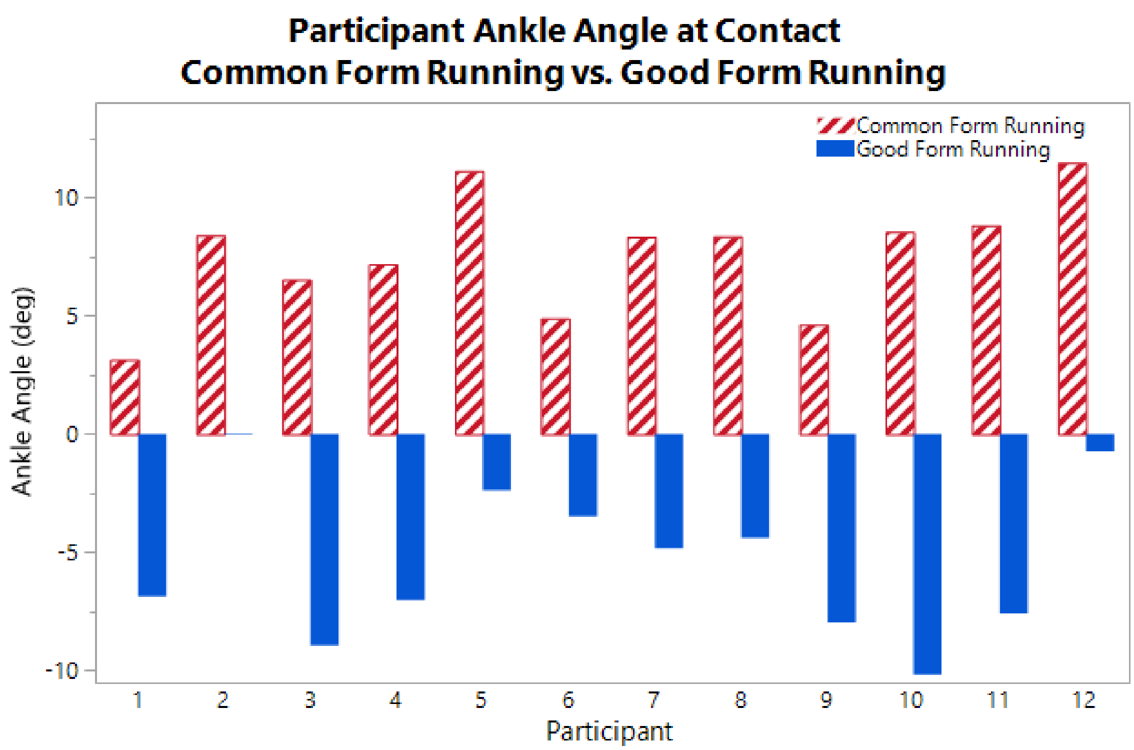

Figure 21: Participant Ankle Angle at Contact for Common Form Running vs. Good Form Running

Since running speed varied by condition, trial speed statistics were executed to observe significant correlations and evaluate how velocity may have effected key variables. Trial speed was determined to be significant between all combinations of conditions ($p_{1\text{-}2} < 0.0001$, $p_{1\text{-}3} = 0.0015$, $p_{2\text{-}3} = 0.0011$). The mean trial speed is displayed in Figure 22 and demonstrates a decrease in speed for runners right after gait retraining, from 3.08 ± 0.27 m/s to 2.52 ± 0.42 m/s, but an increase in speed after one month of training, to 2.8 ± 0.42 m/s. The mean trial speed decreased by 9.1% between conditions 1 and 3. Each participants' average trial speed for condition 1 and condition 3 can be compared in Figure 23. Overall, multivariate analysis concluded trial speed to be correlated to maximum vertical GRF (r = 0.723), maximum horizontal GRF (r = 0.833), and minimum horizontal GRF (r = -0.785). Trial speed was also correlated to maximum horizontal GRF (r = 0.745) in condition 1, maximum vertical (r = 0.765), maximum horizontal (r = 0.882) and minimum horizontal (r = -0.858) in condition 2, and maximum vertical (r = 0.786) and horizontal GRF (r = 0.876) in condition 3.

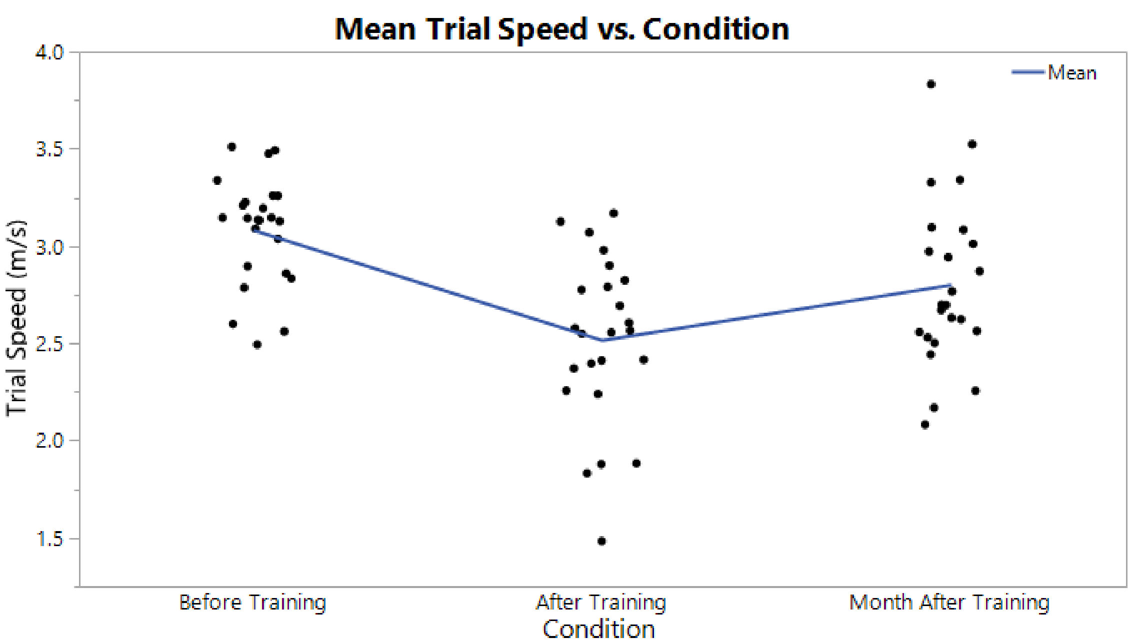

Figure 22: Mean Trial Speed vs. Condition

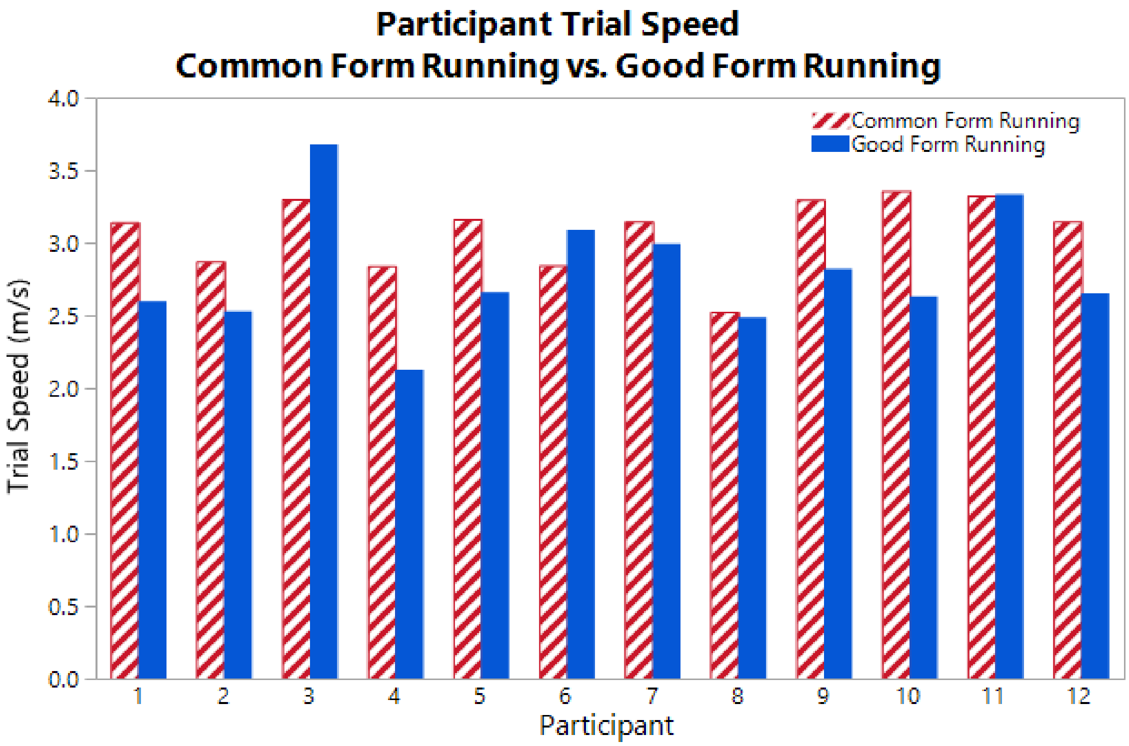

Figure 23: Participant Trial Speed for Common Form Running vs Good Form Running

7 Discussion

The purpose of this pilot study was to quantify a difference between common form running and Good Form Running lower extremity kinematics and GRF's. The results indicate there is a statistically significant difference between the two running forms. Collecting data before training, after training, and one month after training was helpful in understanding how runners responded to the Good Form Running gait retraining in addition to the kinematic and ground reaction force differences.

The force and joint angle graphs in the appendix offer a visual comparison of how individual participants responded to the gait retraining and a comparison for left and right sides of the body. The vertical force graphs show that every participant began with an impact transient in their vertical GRF, associated with high loading rates, but had a smooth bell shaped curve by the final data collection with Good Form Running. The fore-aft force graphs show each participant transitioning from one negative peak with common form to two negative peaks with GFR. The removal of the impact transient in the vertical GRF graphs and the addition of a second peak in the energy absorption phase of the fore-aft GRF graphs indicate a switch from a rearfoot strike pattern to a midfoot strike pattern and a reduction in impact loading (Boyer, Rooney, & Derrick., 2014; Daoud, et al., 2012). Some participants demonstrated subtle visual differences between left and right sides of the body and showed an asymmetric response to training, with one leg assimilating quicker than the other. While joint angles at contact were the focus, the joint angle graphs in the appendix also reveal how each participant modified their kinematics throughout the gait cycle. The shape of the joint angle graphs between conditions remained similar except for the beginning and end of ankle angle where the ankle became more plantarflexed before contact and at contact in the third condition. A visual observation of both force and joint angle graphs may imply the difficulty in transitioning to a new running form and that full adaptation takes time, supporting statements made in section 2.4 (Dugan & Bhat, 2005; Heiderscheit, Chumanov, Michalski, Wille, & Ryan, 2011).

Although all variables were significant between conditions 1 and 2, statistical analysis between condition 1 and condition 3 was the most important for this study because it revealed which variables were significantly different between common form running and Good Form Running. Loading rate, minimum horizontal GRF, knee angle at contact, and ankle angle at contact were all significantly different between common form and Good Form Running, while maximum vertical GRF, maximum horizontal GRF, and hip angle were not.

The mean loading rate in Figure 9 started off very high and drastically decreased between the first and second condition then reduced more between the second and third condition. For each participant the high loading rate, found in condition 1, was associated with an impact transient in the vertical GRF and greatly decreased in condition 2 and 3, when the impact transient was absent. Loading rate was correlated to maximum vertical GRF within condition 1 and condition 3, which was also determined to be linked with risk of injury by Davis et. al (Davis, Bowser, & Mullineaux, 2015). These loading rate results imply that switching to Good Form Running may reduce the risk of obtaining an overuse injury (Daoud, et al., 2012; Larson, 2011).

The mean maximum vertical and mean maximum horizontal GRF graphs in Figure 11 and Figure 13 closely resemble the mean trial speed graph in Figure 22. With the mean minimum horizontal graph in Figure 14 following a similar but inverse trend of decreasing for condition 2 and increasing in condition 3. These observations were reinforced by all GRF variables being significantly correlated to trial speed and supporting conclusions reached by previous studies (Dugan & Bhat, 2005). It is also important to note that while trial speed was correlated with all

GRF variables it was not correlated with loading rate. Implying that loading rate may be independent of running velocity. When trial speed and GRF's decreased in condition 2 it was most likely because participants had just learned the new running form and had difficulty running at their typical training pace. An increase in all variables was seen with condition 3 when participants had practiced for a month and were able to pick up their pace. The minimum horizontal GRF was significantly different between common form and GFR, decreasing by 21.6% after one month of training. This large decrease suggests less braking force slowing the forward motion of center of mass, making it easier to run faster and more efficiently.

There was no significant correlation between any joint angles at contact and trial speed because speed only affects the maximum range of joint angles (Dugan & Bhat, 2005; Nicola & Jewison, 2012; Novacheck, 1998). The hip angle at contact had a lot of variability at all conditions but decreased only at condition 2 to return to a similar value as condition 1 in the third condition. Hip angle was not significant for comparing common form to Good Form but had significant correlation to knee angle for GFR in condition 3. This is most likely related to participants transitioning to GFR and landing with increased flexion in the knee and body leaning forward from the ankles.

Knee and ankle angle at contact were significantly different between all conditions with steady increase or decrease showing development of the new running form and need for at least a one month training program. Mean knee angle at contact, seen in Figure 18, increased significantly with the progression of each condition. This steady increase signifies greater knee flexion at each condition as runners got better at landing with their foot under their hips. Since GFR is characterized by a cadence of 180 steps/min, the increased cadence may also be responsible for helping the foot land under the hips. Ankle angle at contact determines the foot strike pattern used.

The mean ankle angle at contact in Figure 20 shows the movement from common form running to GFR with the transition from dorsiflexion, positive values, to plantarflexion, negative values. A plantarflexed ankle indicates a midfoot or forefoot strike. The ankle angle at contact was significantly correlated to loading rate and is the only kinematic variable correlated to a kinetic variable. This may indicate the importance of ankle angle, or foot strike pattern, as a significant difference between the two running forms and important in reducing loading rate.

No previous research has observed the biomechanics of Good Form Running. This pilot study examined lower extremity kinematics Good Form Running and compared it to common form running. The results of this study have recognized that there are significant differences between common form running and GFR, some of which may imply a reduction in risk of overuse injuries and increase in efficiency. Based on these findings it may be beneficial for a long-distance common form runner to switch to Good Form Running using a gait retraining program. Also, while not a quantifiable part of the study, the feedback received from all participants was positive. Runners felt more efficient in their movements and expressed they could run farther and faster without getting fatigued.

8 Future Research

Good Form Running is described as a midfoot strike, a cadence of 180 strides/min, forward body lean, and an elongated but relaxed posture (Playmakers, 2016). The design of this study ensured participants ran with correct cadence and was able to capture the switch to a midfoot strike. However, only analyzing lower extremity kinematics limited this study from quantifying the body lean and posture of GFR. Future works on this participant should include full body kinematics and a more extensive kinetic evaluation of Good Form Running, to find lower extremity joint moments and powers. The results of this study provide evidence to support that GFR may reduce risk of injury but a running efficiency study should be done to conclude if GFR is more efficient than common form running.

The main limitation of this study and other gait retraining studies, was participant compliance to the one month long training. Another limitation of this study was the inability of the procedure to control for speed. Using a treadmill is still not the best option, since it has been observed to alter running form, but further examination of ground reaction forces should control for running velocity. Since this study was the first biomechanical analysis of Good Form Running, researchers now have a baseline to assess if runners are using GFR. Further examination on the biomechanics of GFR should use a larger sample size to validate the results of this research. The results of this work may also be used for a comparison to other popular running styles like POSE Method and Chi Running.

9 Conclusion

Running studies have been executed to analyze popular running forms but have neglected to evaluate Good Form Running. This pilot study used three-dimensional motion capture and in-ground force plates to quantify differences in sagittal plane lower extremity kinematics and ground reaction forces between common form running and Good Form Running. Data was collected on 12 runners before training, after training, and one month after training. Comparing the two forms revealed a significant difference in loading rate, minimum horizontal ground reaction force, knee angle at contact, and ankle angle at contact. Loading rate and braking force significantly decreased, the knee became more flexed at contact, and the ankle went from dorsiflexed to plantar flexed at contact. Some of these significant differences imply a reduction in risk of overuse injuries and increase in efficiency. Therefore, it may be beneficial for a long-distance common form runner to switch to Good Form Running using a gait retraining program but further biomechanical evaluation of Good Form Running is necessary to fully understand the possible advantages and disadvantages.

9 Appendix

Table A-1: Average and standard deviation of critical variables for all participants at each condition

Subject	Condition	Loading Rate (xBW/s)	Max Vert. GRF (xBW)	Max Horiz. GRF (xBW)	Min Horiz. GRF (xBW)	Hip Angle at Contact (deg)	Knee Angle at Contact (deg)	Ankle Angle at Contact (deg)	Trial Speed (m/s)
1	1	44.808 +/- 4.231	2.316 +/- 0.062	0.299 +/- 0.001	-0.227 +/- 0.001	27.475 +/- 2.209	16.622 +/- 3.238	3.141 +/- 1.307	3.141 +/- .006
1	2	19.904 +/- 1.802	1.951 +/- 0.081	0.139 +/- 0.004	-0.106 +/- 0.017	20.822 +/- 1.352	17.626 +/- 2.535	.183 +/- 2.562	1.657 +/- .174
1	3	24.153 +/- 2.232	2.278 +/- 0.061	0.234 +/- 0.027	-0.210 +/- 0.039	25.091 +/- .293	18.059 +/- .757	-6.864 +/- .222	2.599 +/- .343
2	1	46.995 +/- 5.671	2.262 +/- 0.044	0.297 +/- 0.022	-0.233 +/- 0.035	22.181 +/- .456	16.975 +/- 1.211	8.38 +/- 2.475	2.873 +/- .273
2	2	39.835 +/- 2.604	2.056 +/- 0.019	0.233 +/- 0.004	-0.194 +/- 0.008	18.007 +/- .34	16.717 +/- 1.21	7.431 +/- 2.705	2.553 +/- .003
2	3	27.154 +/- 5.509	2.122 +/- 0.013	0.246 +/- 0.007	-0.211 +/- 0.002	25.81 +/- .083	22.378 +/- .25	.034 +/- .259	2.53 +/- .028
3	1	59.570 +/- 3.700	2.557 +/- 0.011	0.400 +/- 0.008	-0.289 +/- 0.028	25.73 +/- 2.298	15.408 +/- 1.866	6.518 +/- .231	3.301 +/- .173
3	2	33.909 +/- 4.122	2.730 +/- 0.056	0.347 +/- 0.022	-0.331 +/- 0.010	24.653 +/- 1.097	21.218 +/- 1.577	-4.468 +/- .626	3.148 +/- .021
3	3	34.536 +/- 0.230	2.908 +/- 0.023	0.395 +/- 0.038	-0.408 +/- 0.031	27.466 +/- .67	20.354 +/- 2.569	-8.931 +/- .448	3.678 +/- .154
4	1	49.763 +/- 0.298	2.257 +/- 0.041	0.268 +/- 0.009	-0.246 +/- 0.008	31.055 +/- .871	16.5 +/- .829	7.171 +/- 1.403	2.841 +/- .055
4	2	30.347 +/- 2.683	2.161 +/- 0.062	0.227 +/- 0.011	-0.214 +/- 0.009	27.392 +/- 1.322	16.554 +/- 2.637	1.849 +/- .813	2.404 +/- .008
4	3	18.296 +/- 0.747	2.052 +/- 0.073	0.180 +/- 0.000	-0.183 +/- 0.021	29.818 +/- 3.124	22.436 +/- 3.464	-7.024 +/- .158	2.125 +/- .044
5	1	46.751 +/- 0.936	2.298 +/- 0.014	0.347 +/- 0.014	-0.213 +/- 0.001	32.458 +/- 1.313	16.476 +/- 1.839	11.101 +/- .052	3.164 +/- .031
5	2	22.195 +/- 0.258	2.012 +/- 0.025	0.160 +/- 0.003	-0.122 +/- 0.008	24.145 +/- .729	18.758 +/- 1.011	-1.353 +/- 4.126	1.88 +/- .002
5	3	24.313 +/- 1.601	2.220 +/- 0.026	0.198 +/- 0.015	-0.204 +/- 0.014	30.753 +/- 1.26	27.793 +/- .164	-2.395 +/- .531	2.66 +/- .037
6	1	63.022 +/- 2.534	2.319 +/- 0.052	0.249 +/- 0.028	-0.230 +/- 0.027	30.642 +/- .956	20.1 +/- 1.069	4.888 +/- 1.893	2.846 +/- .013
6	2	26.392 +/- 0.075	2.450 +/- 0.045	0.232 +/- 0.013	-0.275 +/- 0.017	31.334 +/- .323	23.965 +/- 1.89	-7.251 +/- 1.381	2.947 +/- .123
6	3	30.690 +/- 0.325	2.467 +/- 0.019	0.153 +/- 0.010	-0.311 +/- 0.012	29.426 +/- .116	27.804 +/- 2.617	-3.486 +/- .592	3.09 +/- .006
7	1	53.992 +/- 5.927	2.498 +/- 0.031	0.295 +/- 0.033	-0.256 +/- 0.002	32.737 +/- 2.665	19.374 +/- 2.204	8.33 +/- 1.472	3.149 +/- .111
7	2	52.495 +/- 3.083	2.408 +/- 0.009	0.273 +/- 0.039	-0.197 +/- 0.008	30.201 +/- 1.206	21.303 +/- 3.032	7.755 +/- .958	2.838 +/- .063
7	3	35.906 +/- 8.878	2.533 +/- 0.034	0.314 +/- 0.027	-0.284 +/- 0.010	31.637 +/- 1.371	24.826 +/- 2.425	-4.825 +/- 1.174	2.992 +/- .019
8	1	45.471 +/- 3.779	2.351 +/- 0.012	0.248 +/- 0.006	-0.175 +/- 0.016	21.017 +/- .549	17.291 +/- 2.791	8.341 +/- .083	2.527 +/- .034
8	2	25.416 +/- 1.379	2.420 +/- 0.031	0.171 +/- 0.020	-0.205 +/- 0.003	18.274 +/- .877	20.398 +/- 1.708	-1.83 +/- 1.721	2.248 +/- .009
8	3	26.795 +/- 0.602	2.492 +/- 0.049	0.201 +/- 0.009	-0.238 +/- 0.033	17.762 +/- .657	20.228 +/- .835	-4.38 +/- .305	2.486 +/- .044
9	1	67.255 +/- 0.520	2.755 +/- 0.121	0.281 +/- 0.001	-0.239 +/- 0.025	20.857 +/- .298	16.333 +/- 1.492	4.626 +/- 3.615	3.299 +/- .04
9	2	29.710 +/- 3.508	2.637 +/- 0.008	0.231 +/- 0.004	-0.207 +/- 0.031	19.688 +/- 1.347	19.23 +/- 1.426	-12.173 +/- .359	2.649 +/- .044
9	3	39.362 +/- 3.567	2.656 +/- 0.011	0.228 +/- 0.015	-0.222 +/- 0.025	19.465 +/- 2.367	17.236 +/- 2.603	-7.964 +/- 3.188	2.819 +/- .052
10	1	50.687 +/- 0.866	2.356 +/- 0.078	0.347 +/- 0.001	-0.292 +/- 0.002	18.055 +/- 1.523	16.478 +/- 3.886	8.528 +/- 3.117	3.359 +/- .133
10	2	18.234 +/- 0.085	2.028 +/- 0.015	0.203 +/- 0.000	-0.211 +/- 0.035	14.99 +/- .093	20.475 +/- 1.819	-4.016 +/- 1.298	2.468 +/- .097
10	3	18.813 +/- 0.557	2.065 +/- 0.035	0.232 +/- 0.028	-0.221 +/- 0.014	19.075 +/- .114	19.999 +/- 1.495	-10.165 +/- 3.995	2.631 +/- .067
11	1	60.757 +/- 2.973	2.567 +/- 0.059	0.319 +/- 0.007	-0.277 +/- 0.020	34.862 +/- 1.407	18.67 +/- .622	8.812 +/- .017	3.327 +/- .183
11	2	32.317 +/- 4.459	2.501 +/- 0.044	0.245 +/- 0.041	-0.241 +/- 0.001	30.474 +/- .072	22.665 +/- 2.258	-3.7 +/- 2.209	2.884 +/- .094
11	3	30.951 +/- 4.147	2.503 +/- 0.079	0.289 +/- 0.034	-0.270 +/- 0.015	33.396 +/- .475	24.361 +/- 1.019	-7.577 +/- 1.119	3.334 +/- .006
12	1	84.187 +/- 2.952	2.650 +/- 0.014	0.303 +/- 0.022	-0.265 +/- 0.009	27.148 +/- 1.633	17.846 +/- .991	11.452 +/- 1.369	3.149 +/- .06
12	2	32.117 +/- 6.199	2.333 +/- 0.054	0.243 +/- 0.005	-0.179 +/- 0.011	23.687 +/- .12	20.15 +/- .515	-5.964 +/- 1.831	2.496 +/- .081
12	3	23.795 +/- 0.667	2.290 +/- 0.012	0.193 +/- 0.007	-0.202 +/- 0.010	26.718 +/- 1.681	24.123 +/- 2.275	-.731 +/- .136	2.651 +/- .02

Table A-2 Correlations within conditions and between all conditions

Correlations within condition 1 - common form running

	Loading Rate (xBW/s) 1	Max Vert. GRF (xBW) 1	Max Horiz. GRF (xBW) 1	Min Horiz. GRF (xBW) 1	Hip Angle at Contact (deg) 1	Knee Angle at Contact (deg) 1	Ankle Angle at Contact (deg) 1	Trial Speed (m/s) 1
Loading Rate (xBW/s) 1	1.0000	0.7186	0.4275	-0.0485	0.1017	0.2501	0.2152	0.3720
Max Vert. GRF (xBW) 1	0.7186	1.0000	0.4308	-0.1504	-0.0417	0.1442	0.1597	0.5323
Max Horiz. GRF (xBW) 1	0.4275	0.4308	1.0000	-0.4718	0.0024	0.0223	0.2343	0.7445
Min Horiz. GRF (xBW) 1	-0.0485	-0.1504	-0.4718	1.0000	-0.0268	0.2078	-0.2216	-0.6516
Hip Angle at Contact (deg) 1	0.1017	-0.0417	0.0024	-0.0268	1.0000	0.4228	0.1562	0.0784
Knee Angle at Contact (deg) 1	0.2501	0.1442	0.0223	0.2078	0.4228	1.0000	0.3597	-0.0289
Ankle Angle at Contact (deg) 1	0.2152	0.1597	0.2343	-0.2216	0.1562	0.3597	1.0000	0.1823
Trial Speed (m/s) 1	0.3720	0.5323	0.7445	-0.6516	0.0784	-0.0289	0.1823	1.0000

Correlations within condition 2 - right after training

	Loading Rate (xBW/s) 2	Max Vert. GRF (xBW) 2	Max Horiz. GRF (xBW) 2	Min Horiz. GRF (xBW) 2	Hip Angle at Contact (deg) 2	Knee Angle at Contact (deg) 2	Ankle Angle at Contact (deg) 2	Trial Speed (m/s) 2
Loading Rate (xBW/s) 2	1.0000	0.3635	0.2172	-0.5135	0.4010	0.0921	0.4808	0.4948
Max Vert. GRF (xBW) 2	0.3635	1.0000	0.7326	-0.6508	0.3712	0.5022	-0.4430	0.7646
Max Horiz. GRF (xBW) 2	0.2172	0.7326	1.0000	-0.7363	0.3162	0.4381	-0.2628	0.8818
Min Horiz. GRF (xBW) 2	-0.5135	-0.6508	-0.7363	1.0000	-0.3785	-0.3142	0.0321	-0.8578
Hip Angle at Contact (deg) 2	0.4010	0.3712	0.3162	-0.3785	1.0000	0.4502	0.0808	0.4387
Knee Angle at Contact (deg) 2	0.0921	0.5022	0.4381	-0.3142	0.4502	1.0000	-0.1439	0.4940
Ankle Angle at Contact (deg) 2	0.4808	-0.4430	-0.2628	0.0321	0.0808	-0.1439	1.0000	-0.1579
Trial Speed (m/s) 2	0.4948	0.7646	0.8818	-0.8578	0.4387	0.4940	-0.1579	1.0000

Correlations within condition 3 - Good Form Running

	Loading Rate (xBW/s) 3	Max Vert. GRF (xBW) 3	Max Horiz. GRF (xBW) 3	Min Horiz. GRF (xBW) 3	Hip Angle at Contact (deg) 3	Knee Angle at Contact (deg) 3	Ankle Angle at Contact (deg) 3	Trial Speed (m/s) 3
Loading Rate (xBW/s) 3	1.0000	0.7480	0.5025	-0.4577	0.1161	0.0535	-0.0159	0.5945
Max Vert. GRF (xBW) 3	0.7480	1.0000	0.7735	-0.5623	0.0372	-0.1199	-0.2684	0.7857
Max Horiz. GRF (xBW) 3	0.5025	0.7735	1.0000	-0.5896	0.2039	0.0307	-0.2100	0.8759
Min Horiz. GRF (xBW) 3	-0.4577	-0.5623	-0.5896	1.0000	-0.2063	0.1676	0.3315	-0.6655
Hip Angle at Contact (deg) 3	0.1161	0.0372	0.2039	-0.2063	1.0000	0.7013	0.2428	0.3093
Knee Angle at Contact (deg) 3	0.0535	-0.1199	0.0307	0.1676	0.7013	1.0000	0.5295	0.0721
Ankle Angle at Contact (deg) 3	-0.0159	-0.2684	-0.2100	0.3315	0.2428	0.5295	1.0000	-0.2616
Trial Speed (m/s) 3	0.5945	0.7857	0.8759	-0.6655	0.3093	0.0721	-0.2616	1.0000

Correlations between all conditions

	Loading Rate (xBW/s)	Max Vert. GRF (xBW)	Max Horiz. GRF (xBW)	Min Horiz. GRF (xBW)	Hip Angle at Contact (deg)	Knee Angle at Contact (deg)	Ankle Angle at Contact (deg)	Trial Speed (m/s)
Loading Rate (xBW/s)	1.0000	0.4579	0.2970	-0.5679	0.2423	-0.3387	0.7199	0.5780
Max Vert. GRF (xBW)	0.4579	1.0000	0.7095	-0.5272	0.1880	0.0699	-0.0575	0.7225
Max Horiz. GRF (xBW)	0.2970	0.7095	1.0000	-0.5996	0.2566	0.1346	-0.0346	0.8331
Min Horiz. GRF (xBW)	-0.5679	-0.5272	-0.5996	1.0000	-0.2778	0.2462	-0.3337	-0.7854
Hip Angle at Contact (deg)	0.2423	0.1880	0.2566	-0.2778	1.0000	0.3999	0.1732	0.3721
Knee Angle at Contact (deg)	-0.3387	0.0699	0.1346	0.2462	0.3999	1.0000	-0.3284	-0.0047
Ankle Angle at Contact (deg)	0.7199	-0.0575	-0.0346	-0.3337	0.1732	-0.3284	1.0000	0.2249
Trial Speed (m/s)	0.5780	0.7225	0.8331	-0.7854	0.3721	-0.0047	0.2249	1.0000

Table A- 3: Matched Pairs Analysis P Values (Prob > |t|)

	Combination of Conditions		
Variables	1 to 2	1 to 3	2 to 3
Loading Rate	<0.0001	<0.0001	0.2298
Maximum Vertical GRF	0.0034	0.2413	0.0095
Maximum Horizontal GRF	0.0029	0.9060	0.0003
Minimum Horizontal GRF	<0.0001	<0.0001	0.2174
Hip Angle at Contact	<0.0001	0.2336	0.0002
Knee Angle at Contact	<0.0001	<0.0001	0.0033
Ankle Angle at Contact	<0.0001	<0.0001	0.0128
Trial Speed	<0.0001	0.0015	0.0011

DAY	Introduction - Week 1	Week 2	Week 3	Week 4	Week 5 - Advanced
Set Up	Posture Reset	Posture Reset	Lean from the ankles	Lean from the ankles	Lean from the ankles
1	Baby Step Jog in place 5 x (1 min. on/1 min. off) 1-2x/day	Baby Step Jog fwd slow 5 x (1 min. on/1 min. off) 1-2x/day	Small Step Jog @ 180spm 4 x (200m in 90 sec. w/ 90 sec. recovery) = 12 min. pace	Med. Step Run @ 180spm 5 x (200m in 60 sec. w/ 60 sec. recovery) = 8 min. pace	High Speed Run @ 180+ spm 4 x (200m in 45 sec. w/ 90 sec. recovery) = 6 min. pace
2	BSJ in place 1 x (1 min. on/1 min. off) 2 x (2 min. on/1 min. off) 1-2x/day	BSJ fwd slow 1 x (1 min. on/1 min. off) 2 x (2 min. on/1 min. off) 1-2x/day	Repeat Day 1	Repeat Day 1	REST
3	BSJ in place @ 180spm 1 x (1 min. on/1 min. off) 2 x (2 min. on/1 min. off) 1-2x/day	BSJ fwd slow @ 180spm 1 x (1 min. on/1 min. off) 2 x (2 min. on/1 min. off) 1-2x/day	SSJ @ 180spm 5 x (200m in 75-90 sec. w/ 90 sec. recovery) = 10-12 min. pace	Repeat Day 2	HSR @ 180+ spm 4 x (200m in 30 sec. w/ 90 sec. recovery) = 4 min. pace
4	BSJ in place @ 180spm 1 x (2 min. on/1 min. off) 1 x (3 min. on/1 min. off) 1-2x/day	BSJ fwd slow @ 180spm 1 x (2 min. on/1 min. off) 1 x (3 min. on/1 min. off) 1-2x/day	Repeat Day 3	MSR @ 180spm 6 x (200m in 60 sec. w/ 60 sec. recovery) = 8 min. pace	REST
5	BSJ in place @ 180spm 1 x (5 min. on/1 min. off) 1-2x/day	BSJ fwd slow @ 180spm 1 x (5 min. on/1 min. off) 1-2x/day	Repeat Day 4	Repeat Day 4	Repeat Day 3
6	Repeat Day 5 - Optional	Repeat Day 5 - Optional	Repeat Day 5 - Optional	Repeat Day 5 - Optional	REST
7	REST	REST	REST	REST	REST
Total Steps	4000-10,000 steps/week	4000-10,000 steps/week			

Figure A-1: Good Form Running Training Sheet

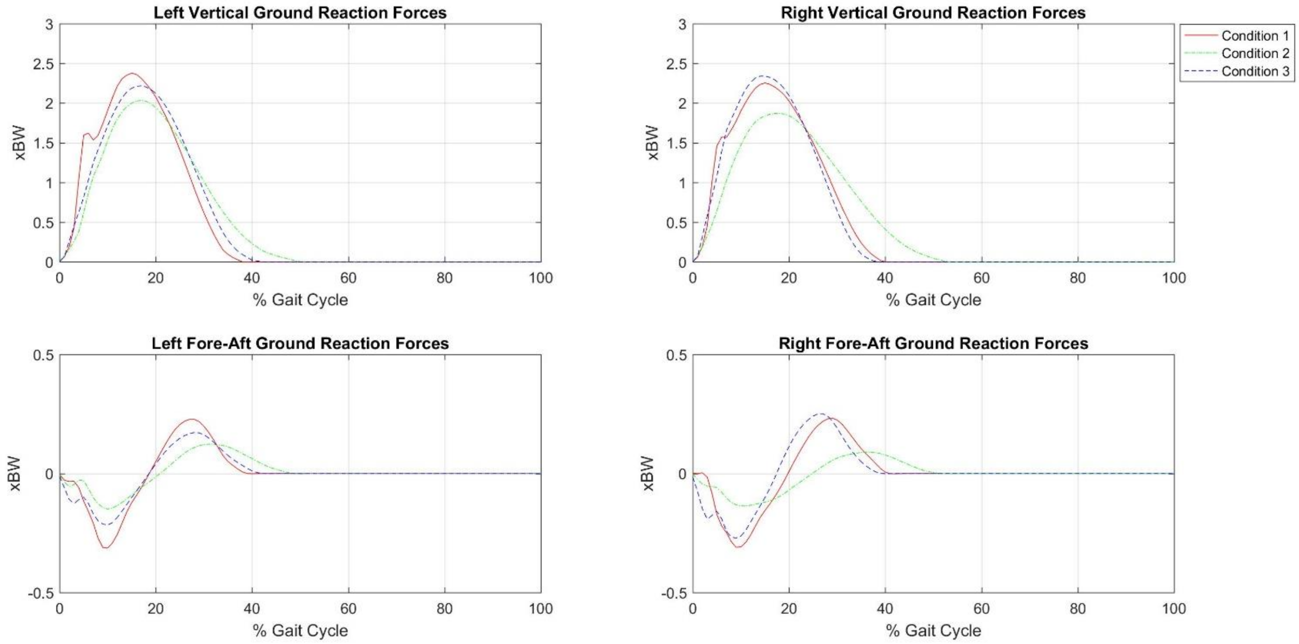

Figure A-2: Participant 1 Force Graphs

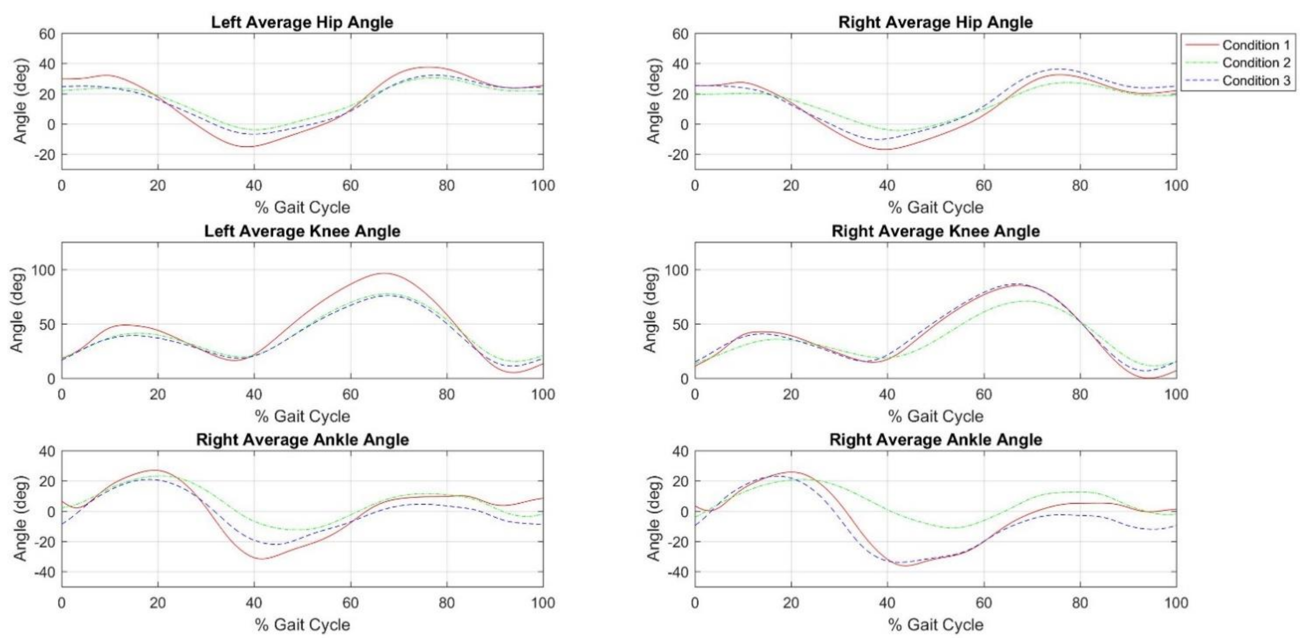

Figure A-3: Participant 1 Joint Angle Graphs

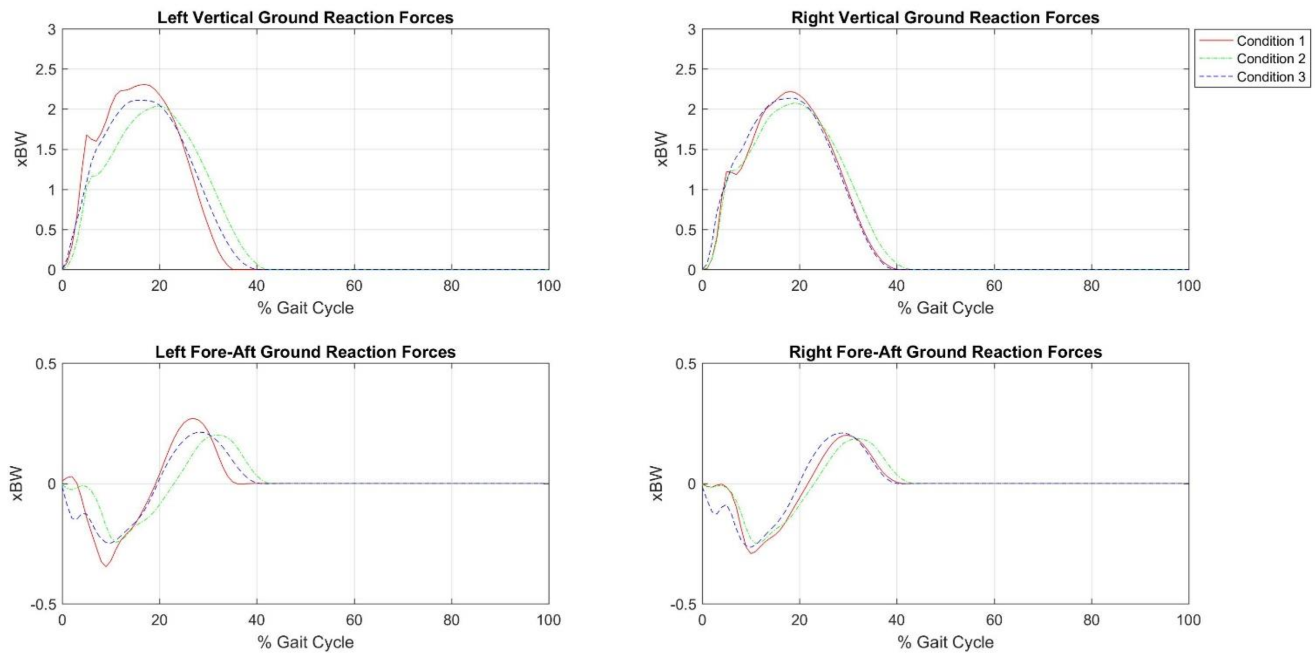

Figure A-4: Participant 2 Force Graphs

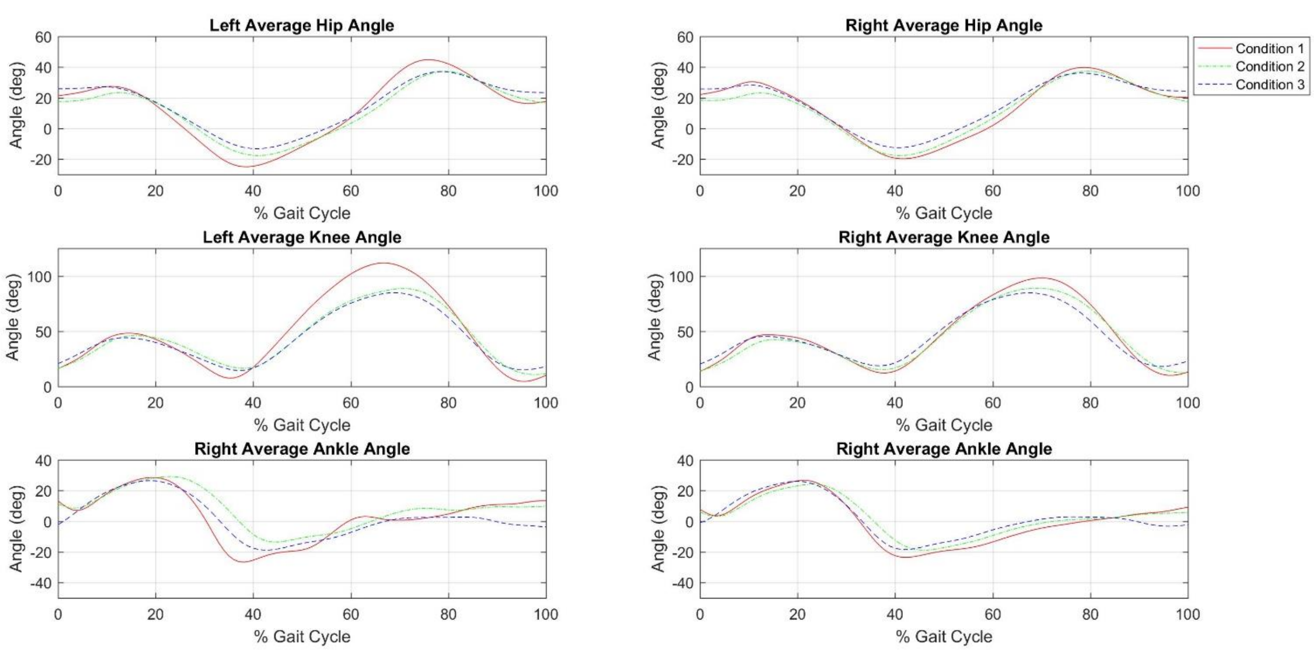

Figure A-5: Participant 2 Joint Angle Graphs

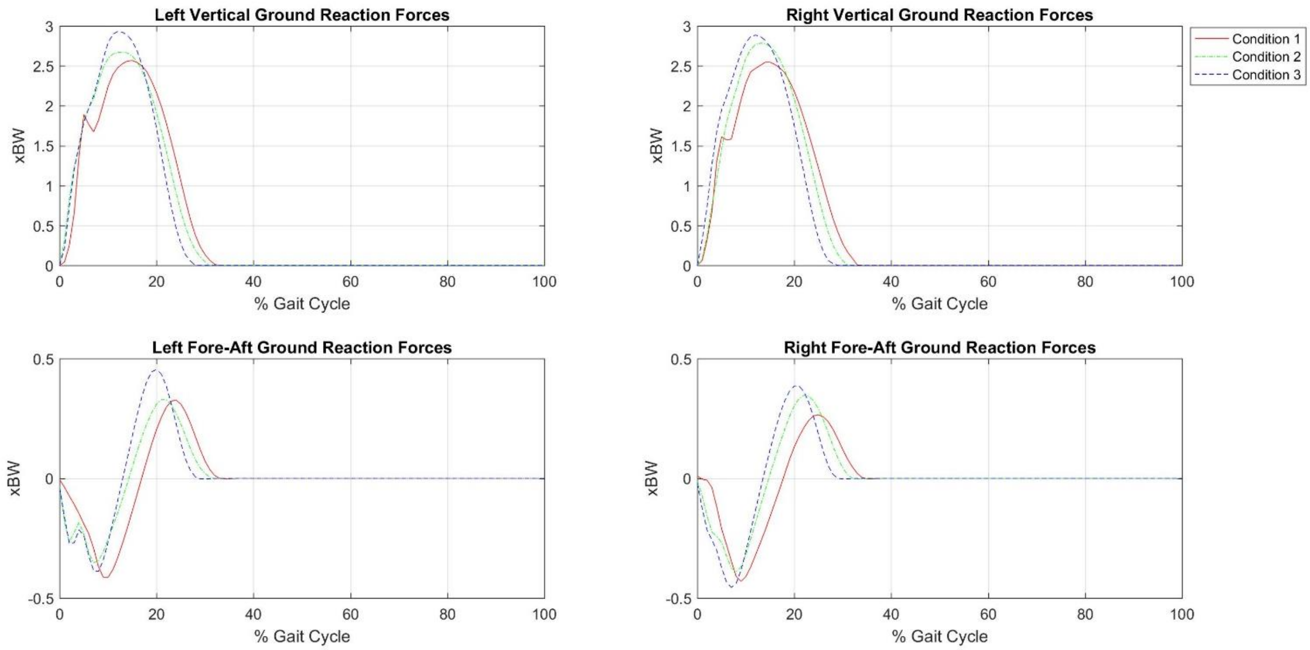

Figure A-6: Participant 3 Force Graphs

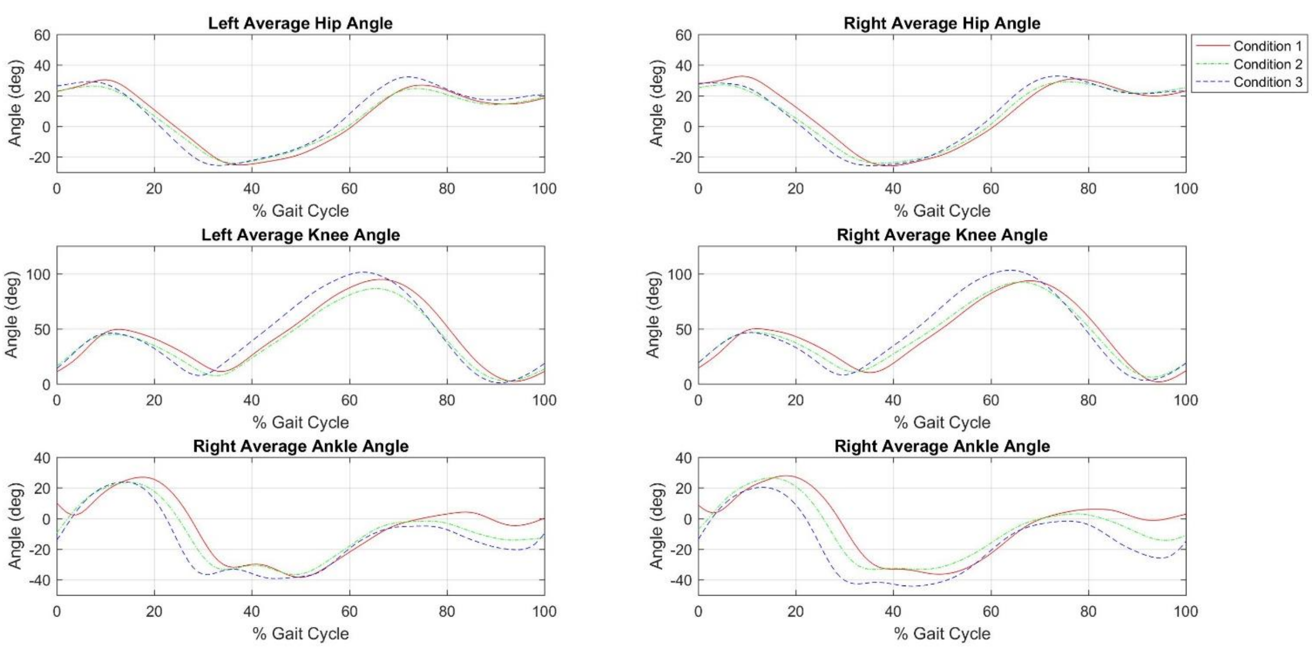

Figure A-7: Participant 3 Joint Angle Graphs

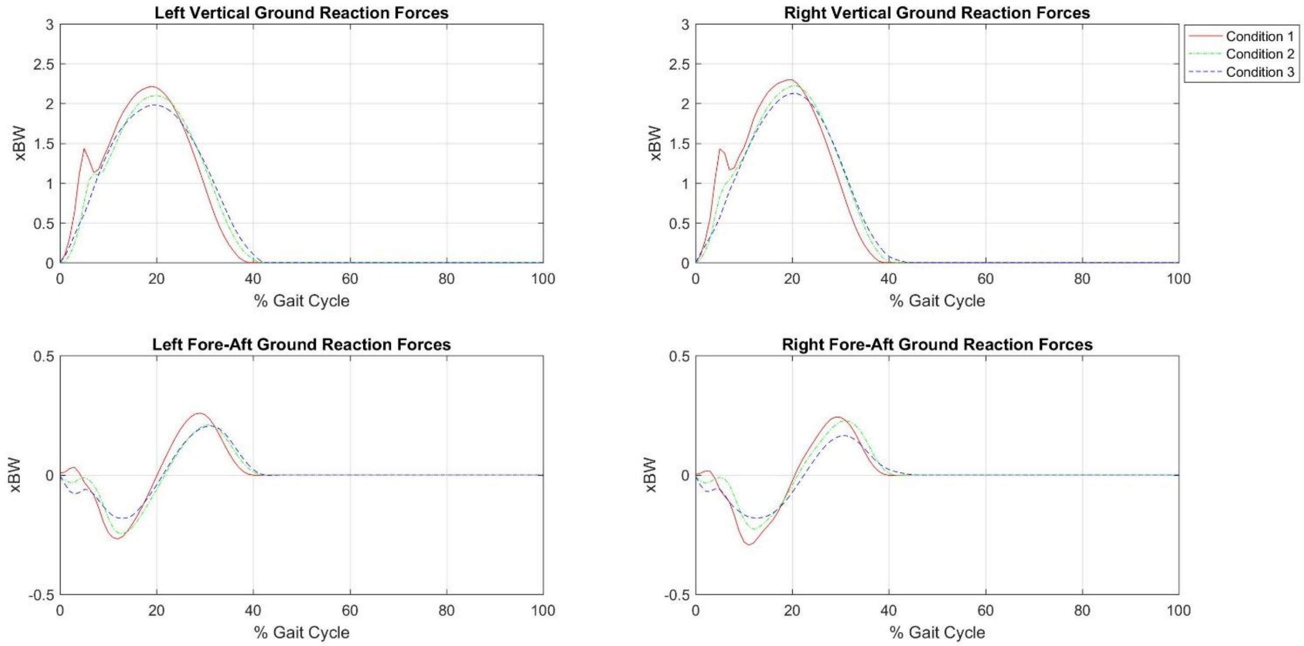

Figure A-8: Participant 4 Force Graphs

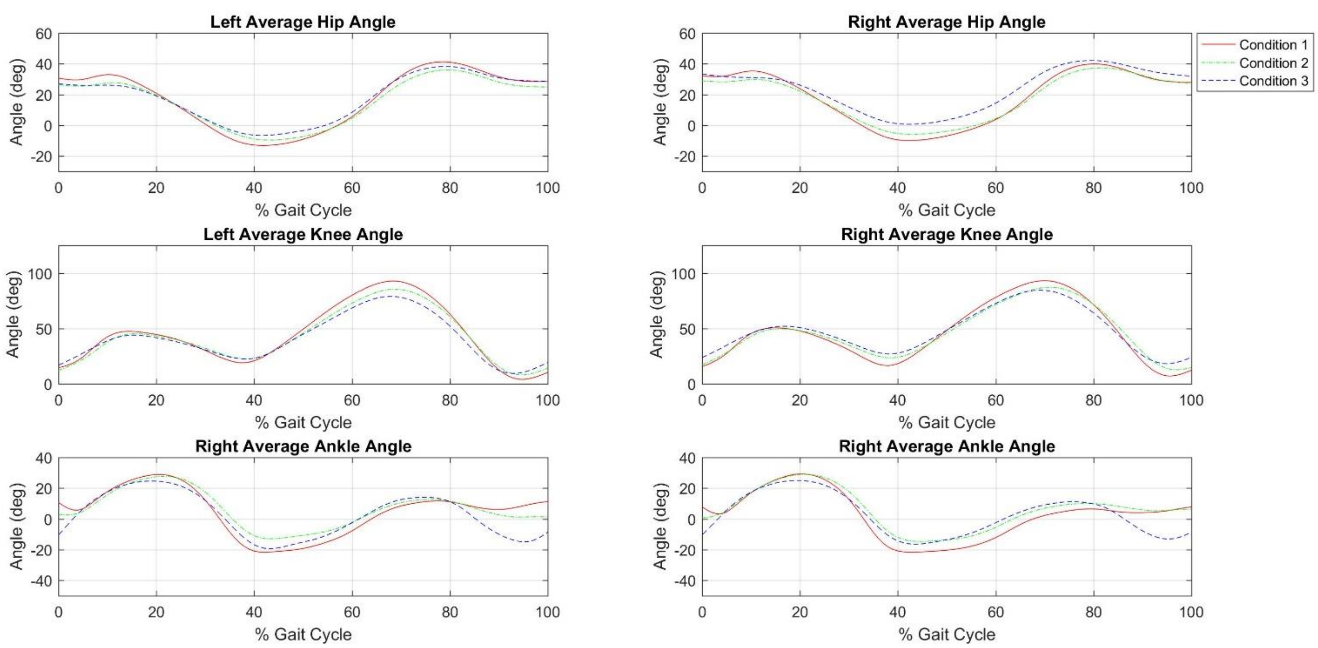

Figure A-9: Participant 4 Joint Angle Graphs

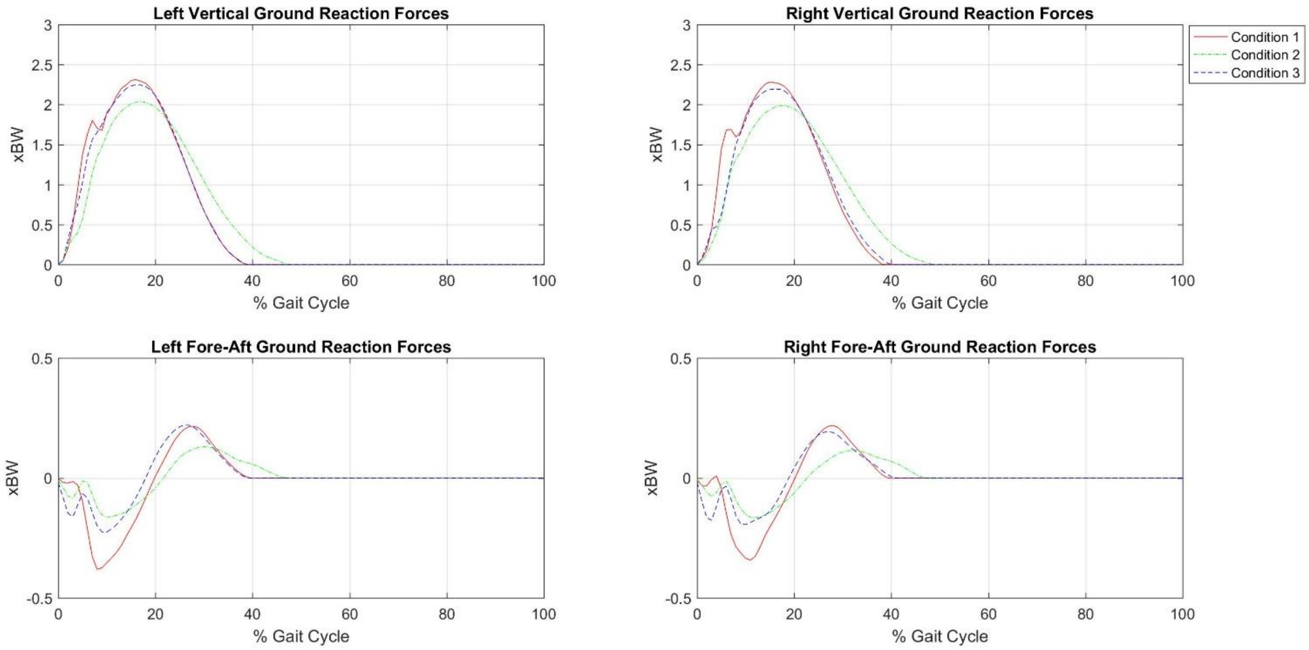

Figure A-10: Participant 5 Force Graphs

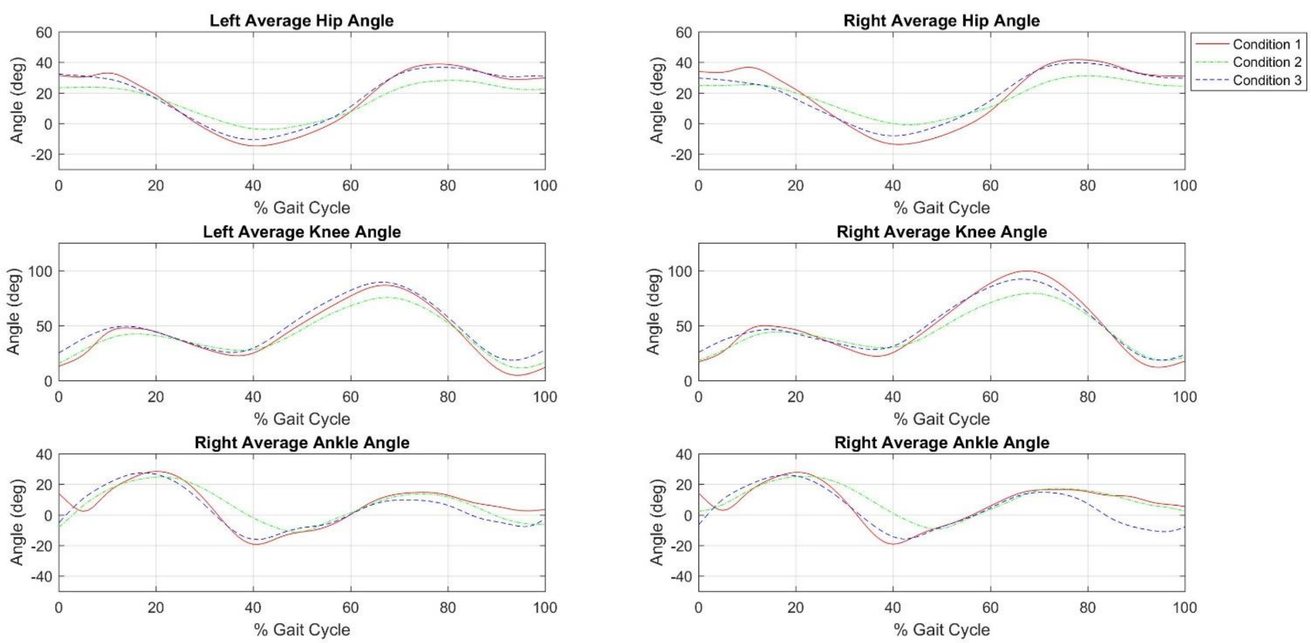

Figure A-11: Participant 5 Joint Angle Graphs

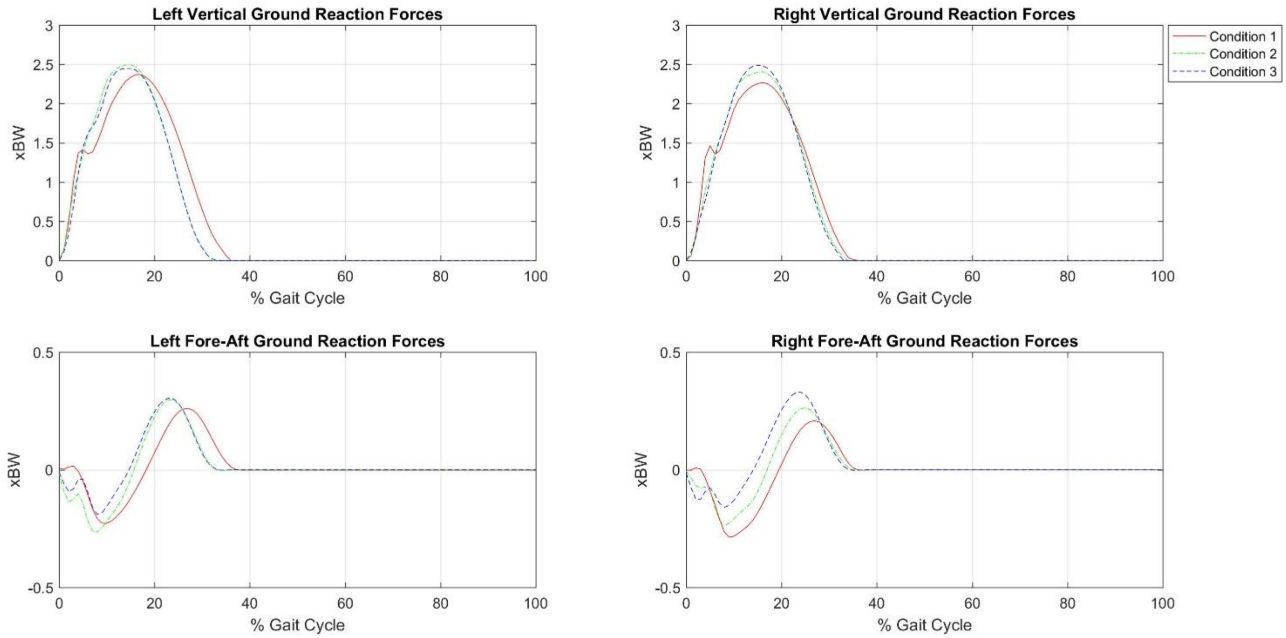

Figure A-12: Participant 6 Force Graphs

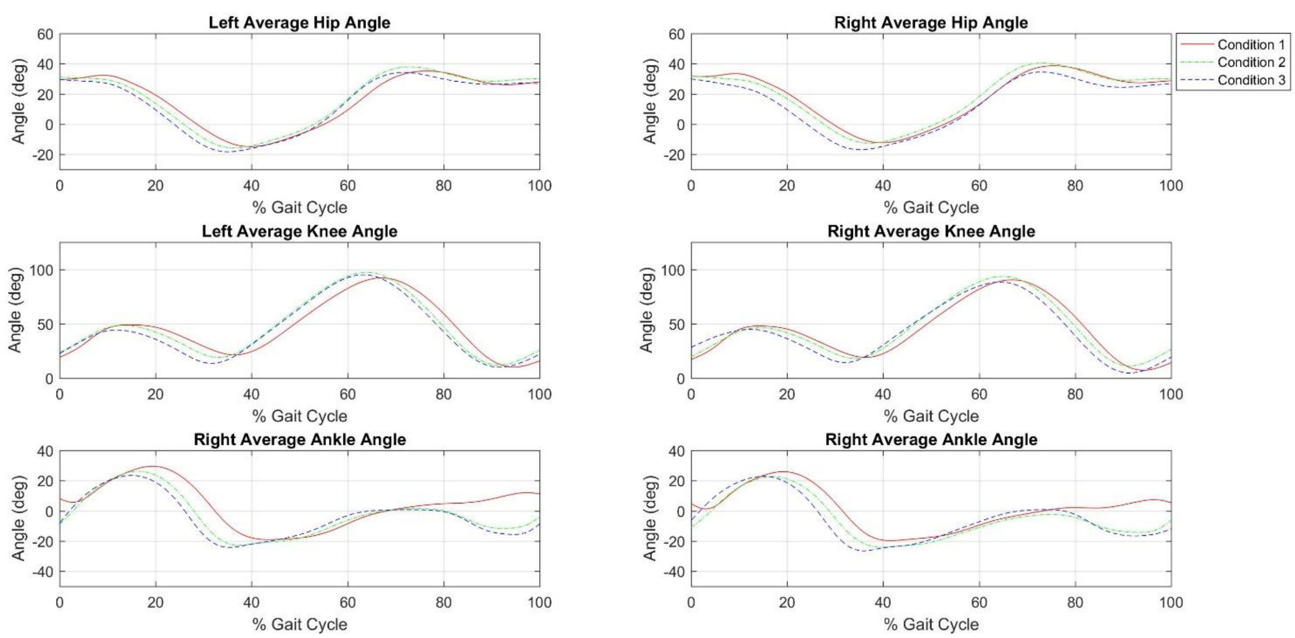

Figure A-13: Participant 6 Joint Angle Graphs

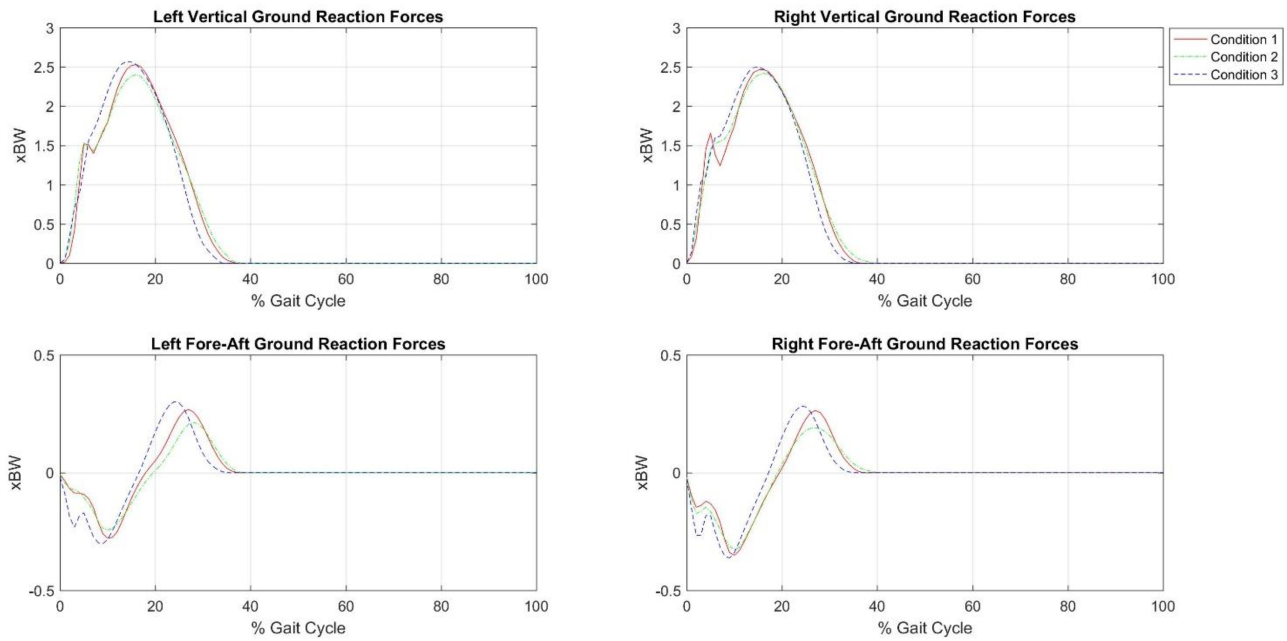

Figure A-14: Participant 7 Force Graphs

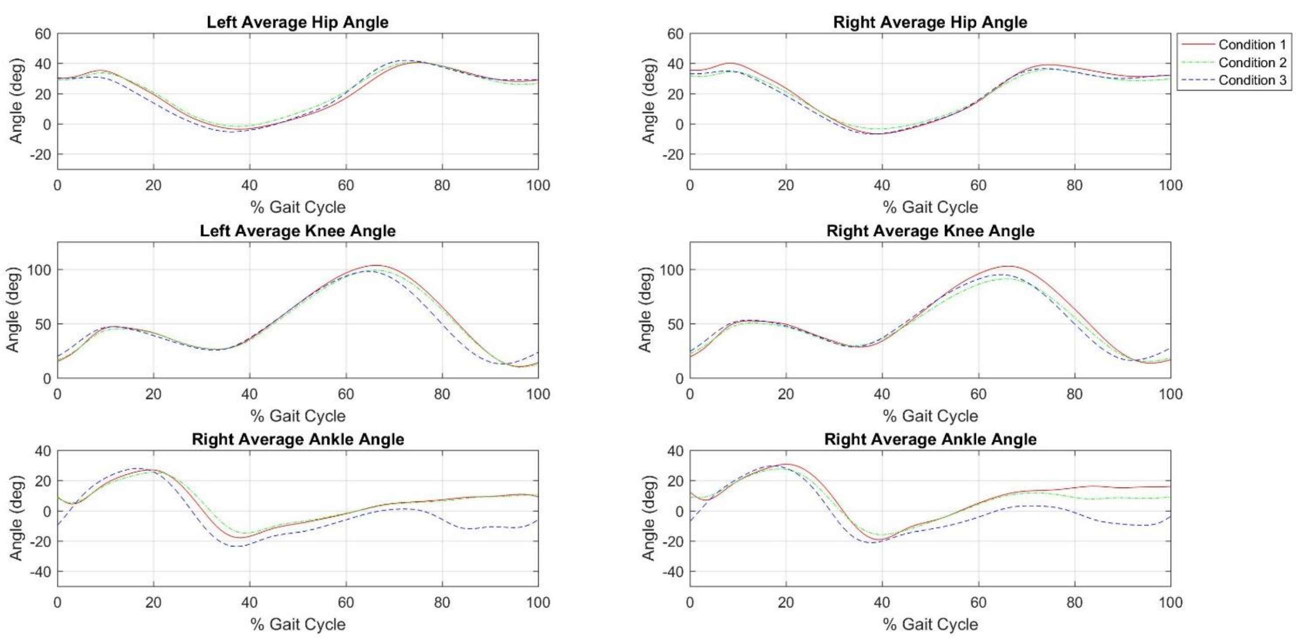

Figure A-15: Participant 7 Joint Angle Graphs

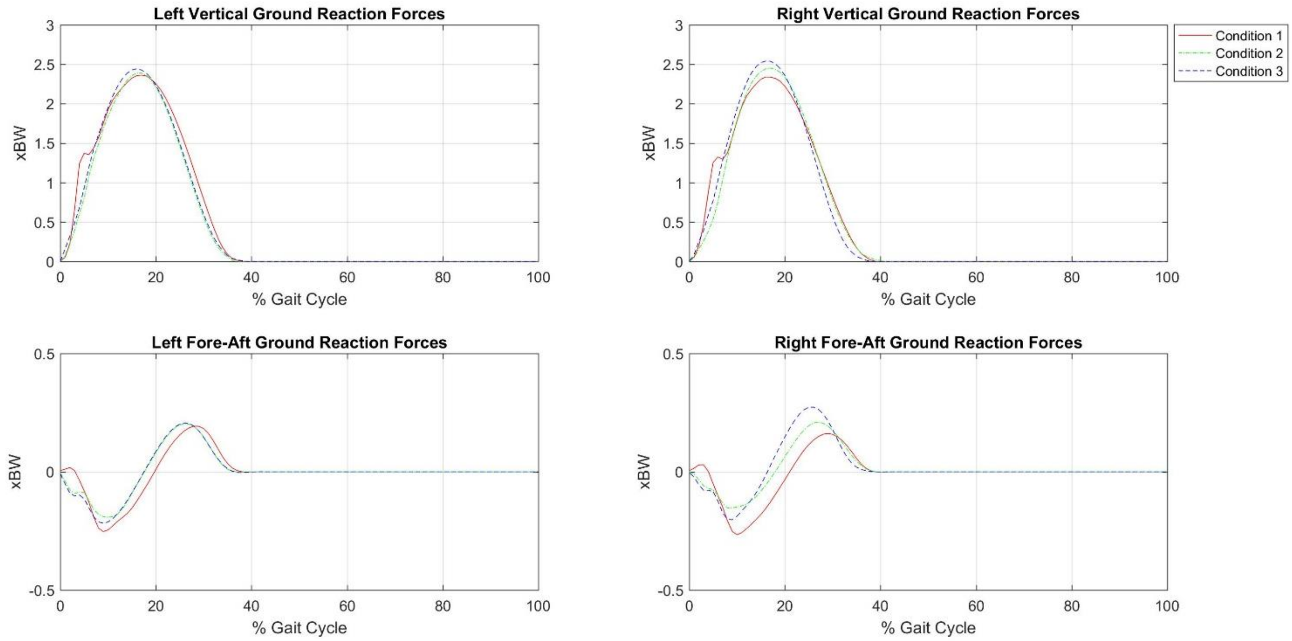

Figure A-16: Participant 8 Force Graphs

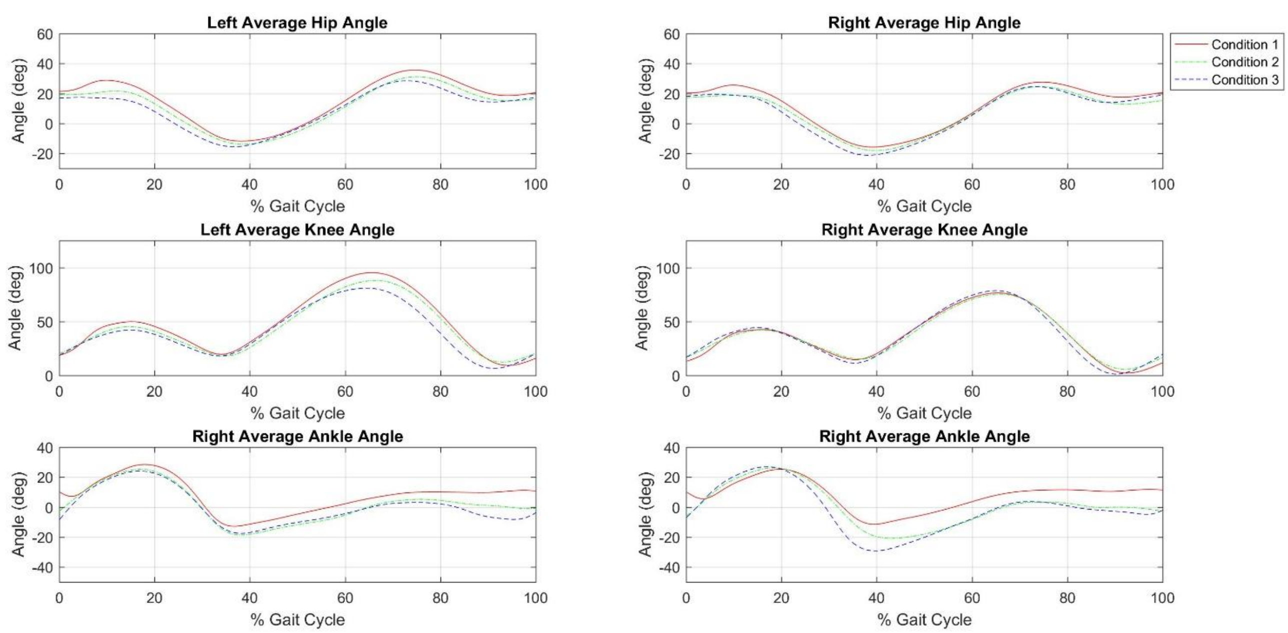

Figure A-17: Participant 8 Joint Angle Graphs

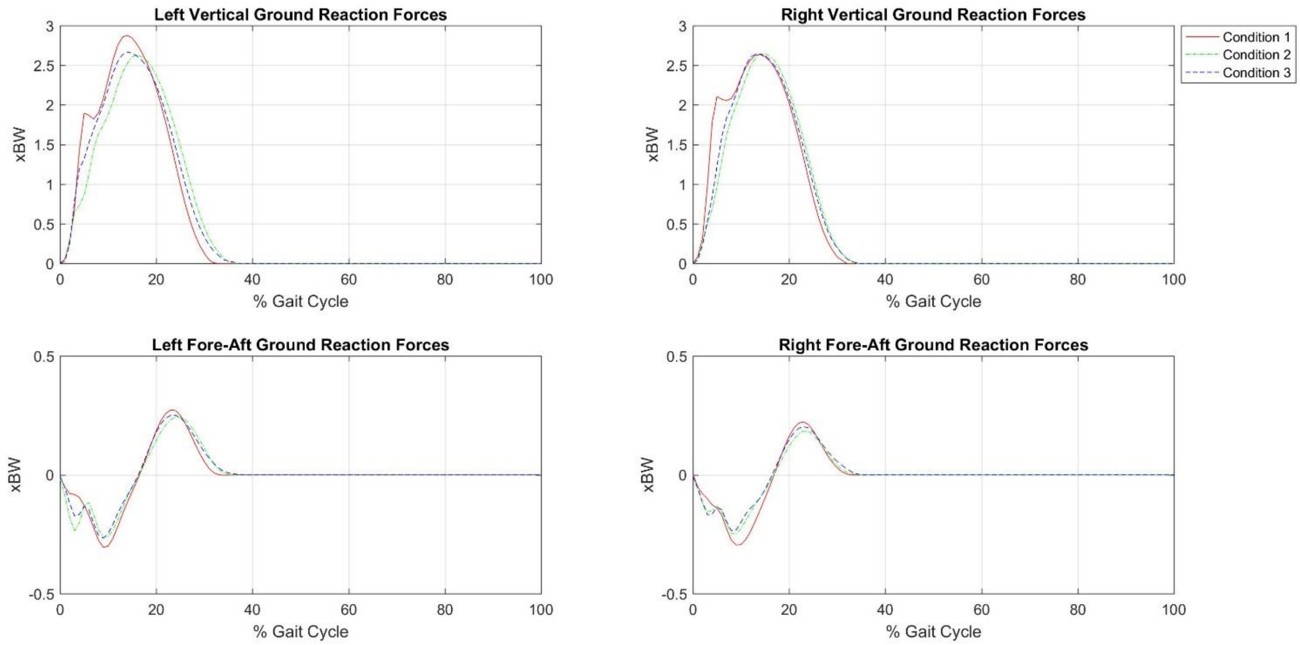

Figure A-18: Participant 9 Force Graphs

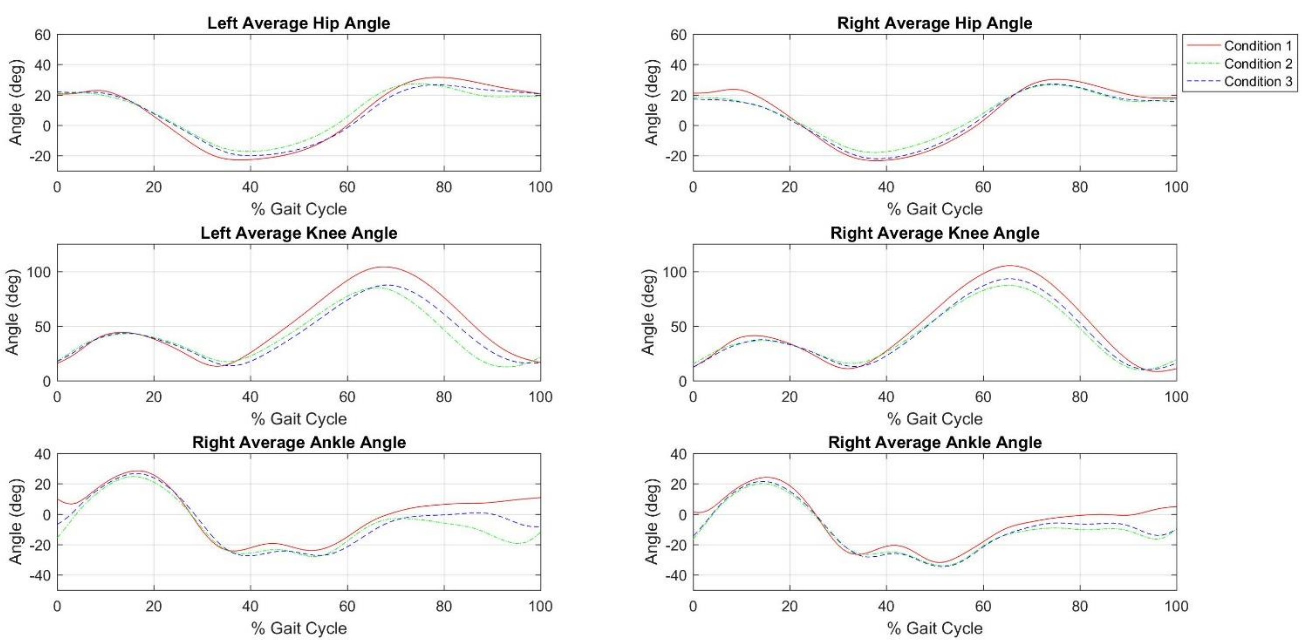

Figure A-19: Participant 9 Joint Angle Graphs

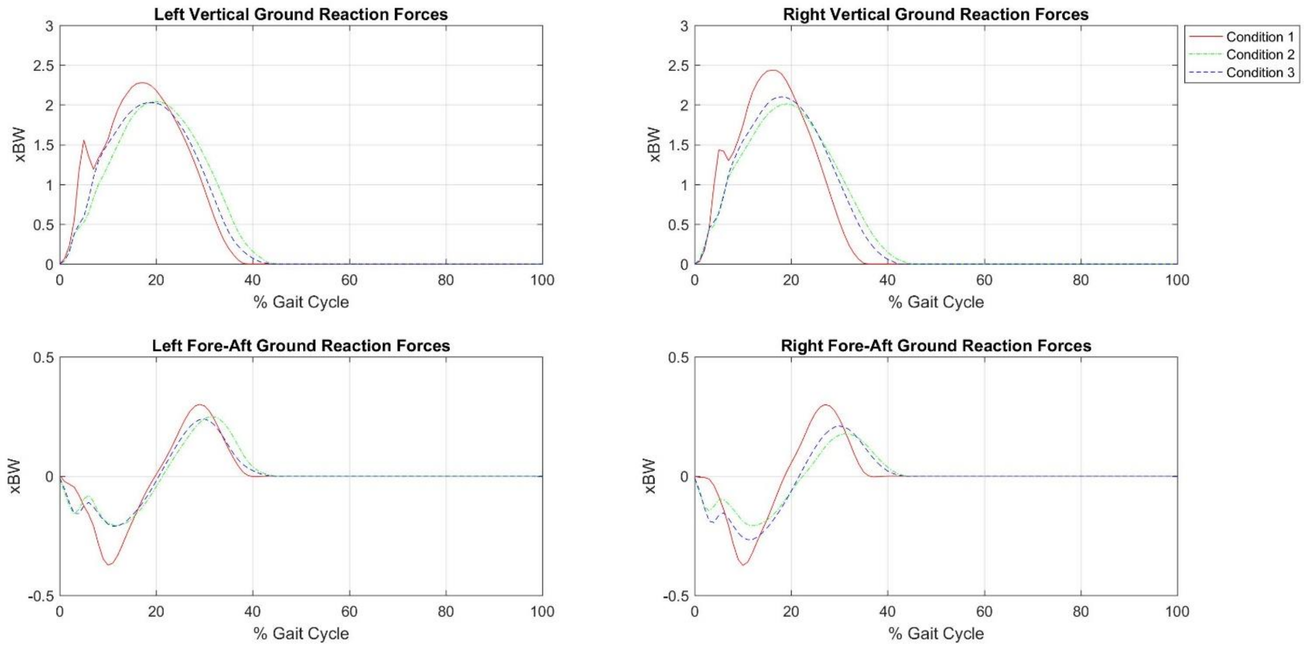

Figure A-20: Participant 10 Force Graphs

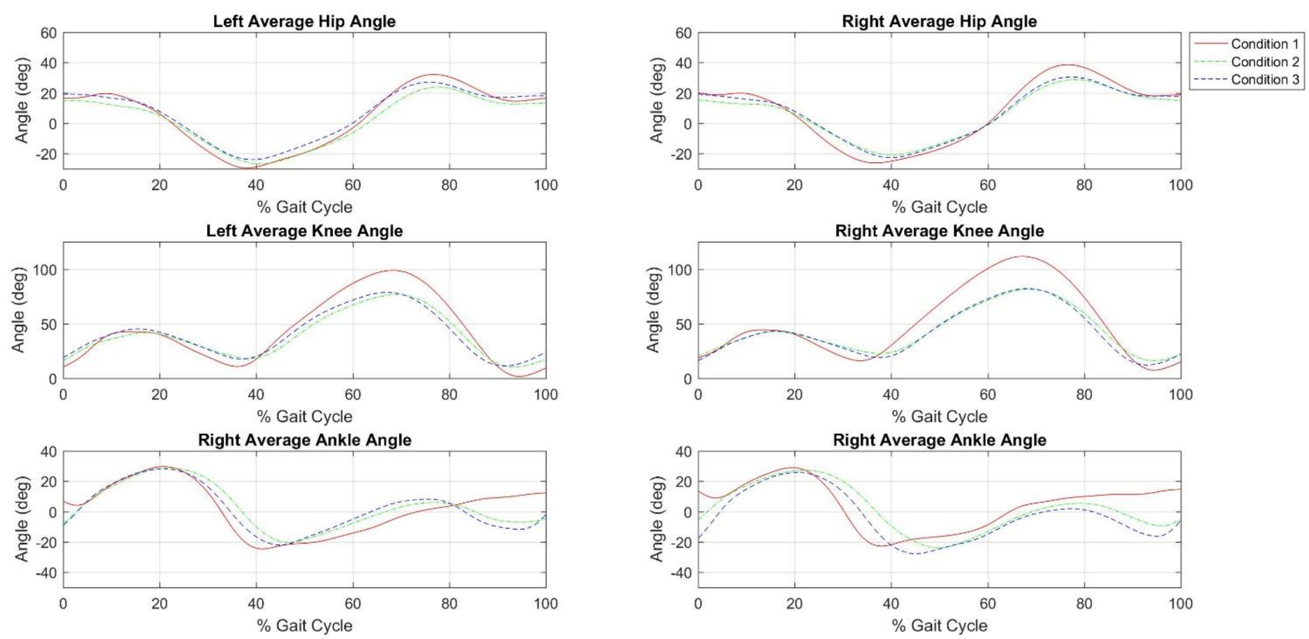

Figure A-21: Participant 10 Joint Angle Graphs

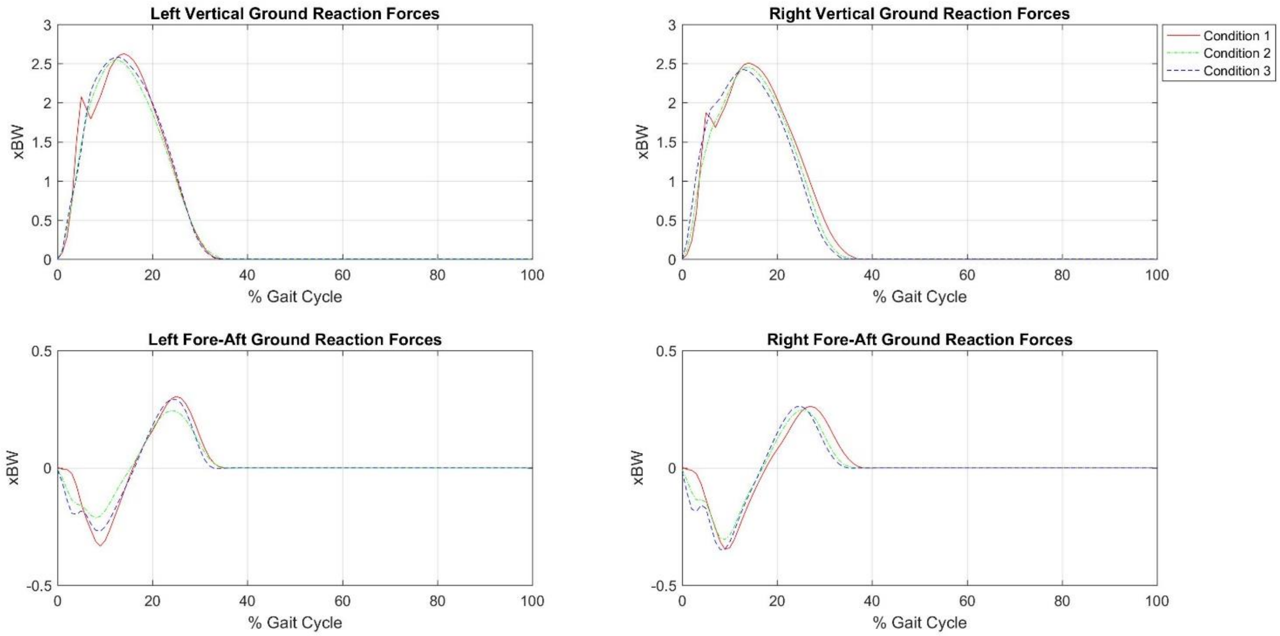

Figure A-22: Participant 11 Force Graphs

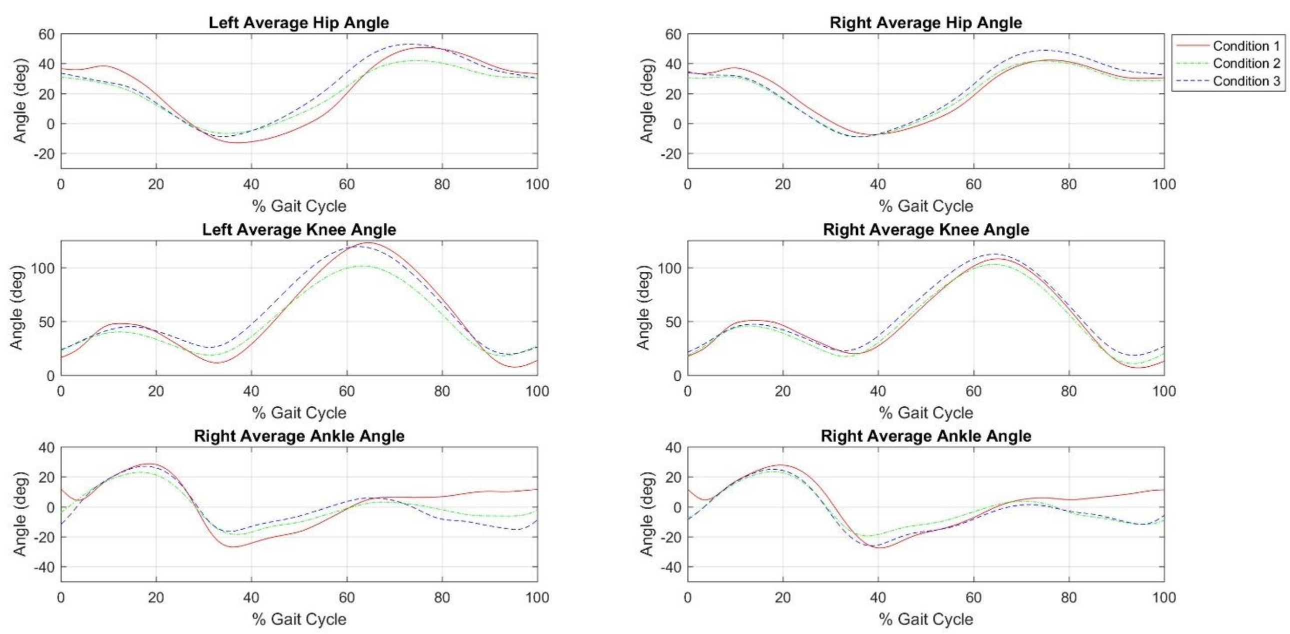

Figure A-23: Participant 11 Joint Angle Graphs

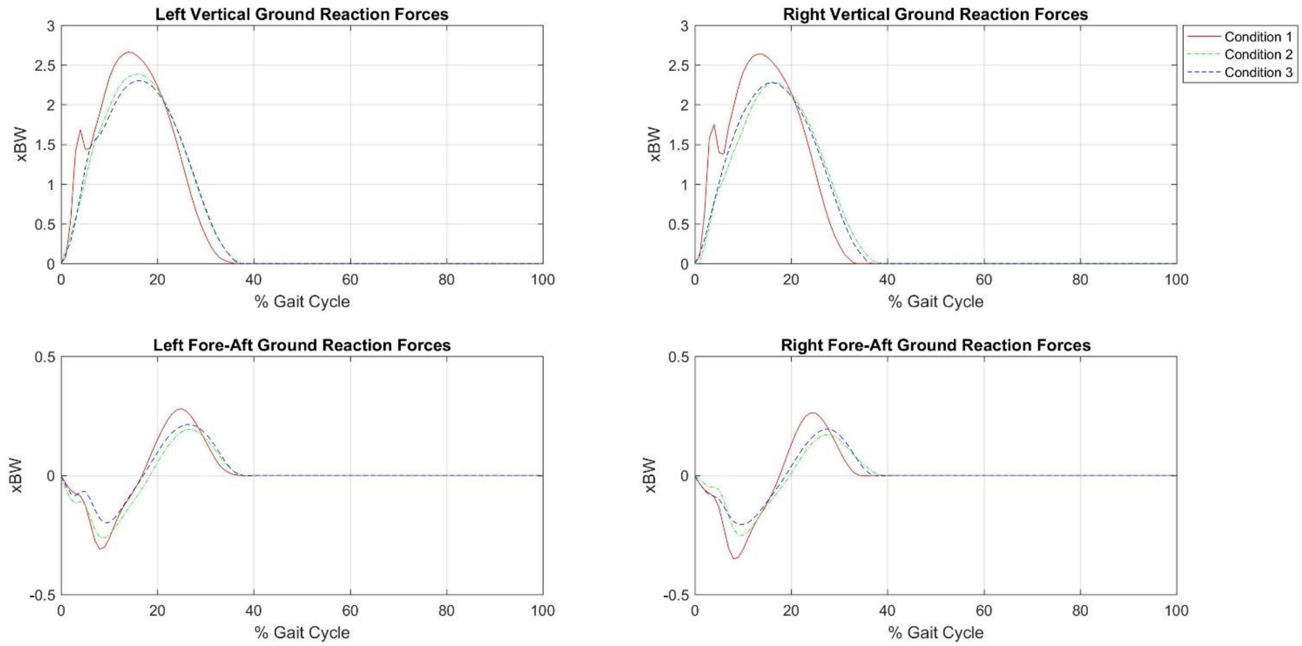

Figure A-24: Participant 12 Force Graphs

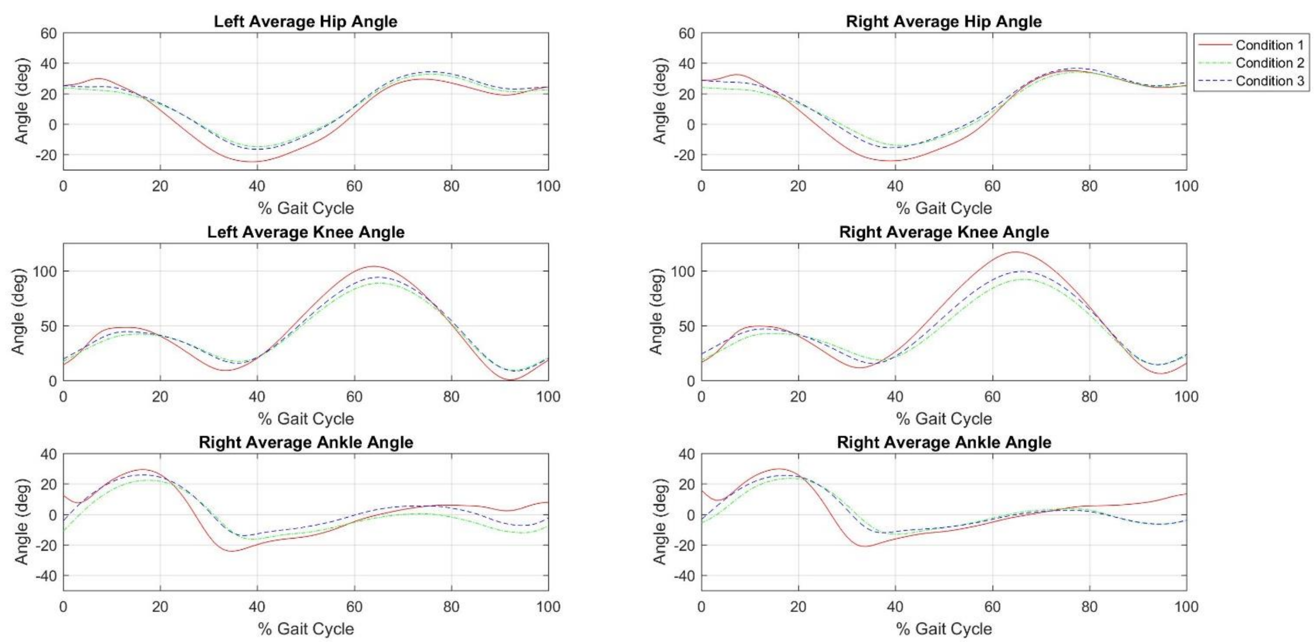

Figure A-25: Participant 12 Joint Angle Graphs

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