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Comparison of Ground Reaction Force in Treadmill Walking and in Overground Walking

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COMPARISION OF GROUND REACTION FORCE IN TREADMILL WALKING AND IN OVERGROUND WALKING

By

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Treadmills prove to be useful in gait analysis and in rehabilitation. Acquiring instrumented treadmills with built in force plate(s) to measure the Ground Reaction Force (GRF) may not be financially feasible for many general purpose biomechanics laboratories; additionally some instrumented treadmills only measure the vertical component of GRF. To provide a solution for such situations, this study examined a method by which the components of GRF are measured through placing a treadmill over floor-mounted force plates. The GRF measured during the treadmill walk was compared to GRF measured in overground walking to validate the method and then to develop a set of equations to be used in predicting the components of GRF when using none instrumented treadmills. A total of twelve male subjects participated in this study. The analysis of the data did not reveal statistical differences in the early-stance and mid-stance peaks of GRF (VGRFP1, VGRFP2, APGRFP1, APGRFP2, and MLGRFP1) between treadmill and overground walking ($p < 0.05$). Statistical differences between treadmill and overground walking were found during late-stance peaks of GRF (VGRFP3, and MLGRFP2) ($p < 0.05$). In late-stance, vertical GRF peaks and medial-lateral GRF peaks were less in treadmill walking than in overground walking by 5–6% and by 1–2% respectively. Regression equations were developed to estimate associations between GRF in treadmill walking and measurements obtained in overground walking.

Dedication

This thesis is dedicated to my dear friend and brother Dwayne C. Leonard. True friends are hard to find, difficult to leave, and impossible to forget. Rest in peace my true friend, rest in peace Dr. Leonard.

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Chapter 1
Introduction

Gait is defined as the arrangement in which limbs move during locomotion. The manner or style a person stands walks or runs is called his/her gait. Standing, walking and running properly involve a sequence of complex actions; during which our bodies integrate sensory feedback from several systems of the body to properly control and coordinate muscles to prevent us from falling. Diseases which can occur in any area of the body, but mainly in the visual, somatosensory, and vestibular systems, may cause gait abnormalities. Gait problems can also arise from bone deformities, movement restrictions, muscle weakness, nerve dysfunction, skeletal or joint misalignments, complications from spasticity or contracture, and complications from arthritis.

Gait analysis is a descriptive tool that can help show how the systems of the body contribute to the way one stands, walks or runs and can help determine underlying problems. It is an investigation of biomechanical abnormalities which may result from one's body compensating for gait problems. A detailed analysis of the way an individual stands, walks and runs can reveal the source of muscle, nerve or skeletal problems. Engineers and medical professionals use gait analysis to assist physicians in determining orthotic or prosthetic recommendations or modifications, as well as physical therapy treatments. The objective data provided by gait analysis enables doctors and surgeons to differentiate between medical conditions which result in walking difficulties, to make confident recommendations for surgical and medical treatments, and afterwards to monitor patient progress and objectively evaluate different treatments. It may also help in deciding whether or not surgery is needed.

Gait analysis allow for “frame by frame observation of motion, kinetics and kinematics” enabling further insights into joints motion. During gait analysis “Joint motion, electromyographic activity of the muscles, and the forces both created by and acting upon the body during human locomotion can be precisely recorded, measured and evaluated.” Also “these measurements may be coordinated in time” giving researchers and physicians that ability to “compare between modes of evaluation” (such as the walking on a treadmill versus overground walking), and thereby recommendations “creating an accurate assessment of a person’s ambulatory ability.” (www.motion-labs.com) This quantitative method utilizes motion capture systems, electromyography, and force platforms to identify gait abnormalities, after which a treatment can be recommended.

Gait measurement is centered around investigating the nuances of a person’s *gait cycle*, sometimes referred to as *stride*. One entire cycle is composed of two phases—*stance* and *swing*—and includes the motions involved between one foot striking the ground and the same foot striking the ground again during walking or running (Figure 1.1). Stance is defined as the initial contact of the foot when the heel touches the ground (0% of a gait cycle) through to the point in time when the toes leave the ground. The stance phase represents about 60% of the gait cycle. The swing phase reflects the time between the toes leaving the ground and the foot making contact again—in other words, the time the foot is not in contact with the ground. The swing phase represents approximately 40% of a gait cycle—that is, the foot is in the air for about 40% of a gait cycle (Gage 1991).

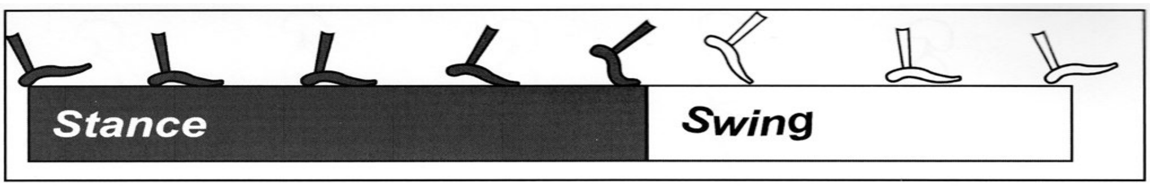


Figure 1.1: Division of Gait Cycle. The shaded bar represent the duration of stance. The clear bar is the duration of swing. Limb segments show the onset of stance with Initial Contact, end of stance by the roll-off of the toes, and end of swing as the instant before the foot contacts the ground. (Perry 1992)

Gait cycle also takes into account the period of time when both feet are in contact with the ground. Periods of *double* and *single support* refer to the time when both feet are on the ground and the time when only one foot is on the ground, respectively (Figure 1.2). There are two periods of double support during the gait cycle, one occurring at the beginning of the stance phase and the other at its end. These two periods of double support are called initial and terminal double-limb stance (Perry 1992).

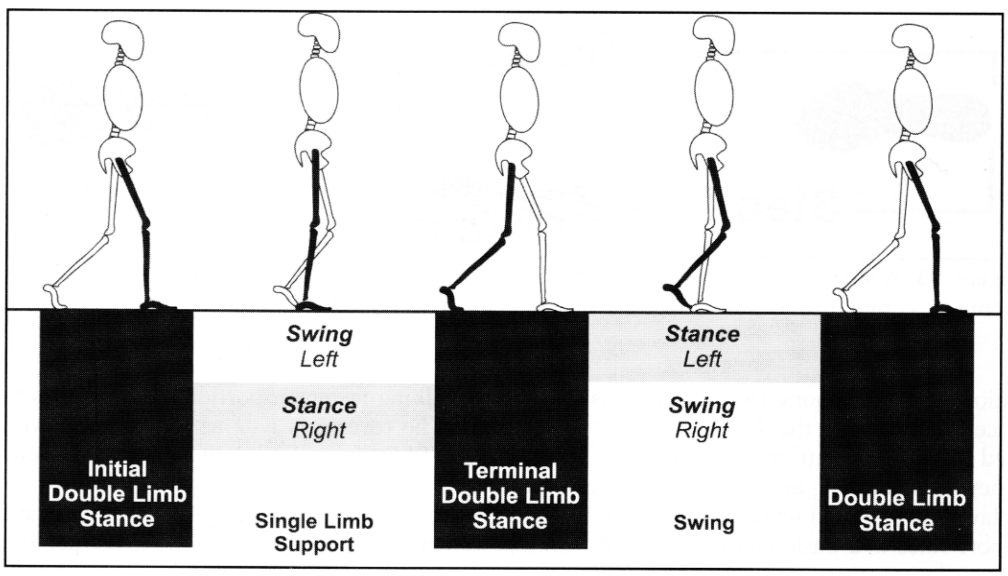


Figure 1.2: The subdivisions of stance and their relationship to the bilateral floor contact pattern. Vertical dark bars are the periods of double limb stance (right and left heel). Horizontal shaded bar is Single Limb Support (single stance). Total stance includes 3 intervals: the initial double stance, SLS, and the next (terminal) double stance. Note that right SLS is the same time interval as left swing. There is a left SLS during right swing. The third vertical bar (double stance) begins the next GC. (Perry 1992)

Ground reaction forces (GRFs) develop during gait as a result of the force applied to the ground when the foot is in contact with it. GRF is equal and opposite to the force that the foot applies on the ground. Since GRF is an external force acting on the body during locomotion, it is of great interest to gait analysis.

The vector associated with GRF (called GRFV) is different from the gravity line. The latter is a vector that extends vertically from the center of gravity of a static body. GRFV, on the other hand, is a "reflection of the total mass-times-acceleration product of all body segments and therefore represents the total of all net muscle and gravitational forces acting at each instant of time over the stance period" (Winter 1984). GRFV can be visualized by studying laboratory investigations of normal gait that employ force platforms to measure GRFV's three-dimensional characteristics (Durward, Baer et al. 1999).

When a foot is in contact with the ground, for example, vertical as well as shear (horizontal) forces are produced. The vertical force results from body weight (BW), and shear forces are due to friction between the foot and the ground. Just as body weight acting downwards generates an equal and opposite upward ground reaction, a shear force that acts anteriorly on the ground causes an equal and opposite posterior reaction. The three components of GRFV during gait are vertical force (F_z), anterior/posterior force (F_{AP}), and medial/lateral force (F_{ML}) (Watkins 2007).

F_z is the largest component of GRF and accounts for the acceleration of the body's center of mass in the vertical direction during locomotion. A typical plot of the vertical ground reaction force through one gait cycle is sometimes called the M curve because it resembles the shape of that letter (refer to Figure 1.3). F_z reaches a maximum of 120% body weight (BW) during the double stance phase and drops to about 80% BW during single stance.

F_{AP} starts as a braking force from the onset of the stance phase to midstance, and then it turns into a propulsion force. It usually represents a sine wave curve with amplitude of 25% BW. As shown in Figure 1.3, it is comprised of two distinct phases—braking phase and propulsion phase—with each phase occurring over approximately 50% of the contact time.

F_{ML} is of lower magnitude in most situations and relates to balance during gait. F_{ML} initially acts in the medial direction with a magnitude of 10% BW or less and then acts laterally during the balance of the stance phase. Changes in medial/lateral velocity are caused by F_{ML}.

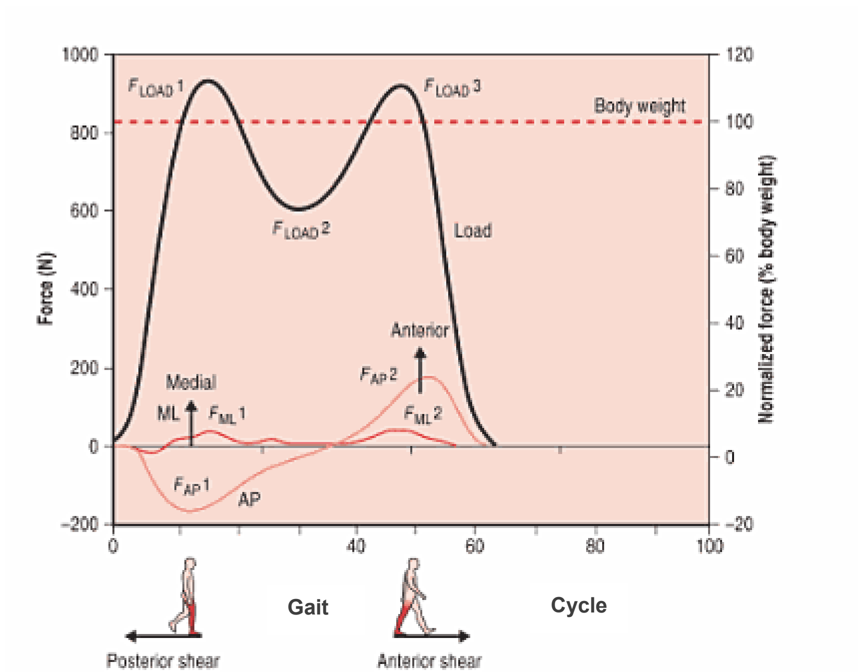


Figure 1.3: The three components of GRF during normal gait.
F_z, the vertical component of GRF, is here referred to as F_{LOAD}. F_{AP} represents the anterior/posterior force component of GRF, and F_{ML} its medial/lateral component.
Adapted from (Kirtley 2006)

Measurement of GRF is critical to gait analysis. To evaluate the GRF exerted as a person walks, it is common to use at least one force plate (aka a force platform) in gait analysis. Floor- mounted force plates accurately measure the three components of GRF as well as moment components. A force plate is usually mounted flush with the floor of a gait laboratory. Data collection with floor-mounted force plates can be a tedious process. The plate is often hidden from the subject's view so that the person does not attempt to alter their gait as they step on the plate. For data to be useful, however, the subject must step entirely on the force plate with one foot only. If the subject misses the force plate completely or partially, or has contact of both feet on the force plate, the measurement is not useful and must be repeated.

Oggero et al. recognizes the necessity of proper foot placement on a force plate as a weakness in gait analysis(Oggero, Pagnacco et al. 1997). In recent years, developments in instrumented treadmills have shown promise as a means of overcoming the limitations of standard gait analysis techniques. Treadmills are often used in research projects to simulate overground locomotion, assuming that overground locomotion is similar to that on a treadmill.

Instrumented treadmills measure forces by using at least one force plate built under or into the treadmill structure. Such treadmills were developed by research groups in gait laboratories but have been emerging into the commercial market in the form of private labs. Use of instrumented treadmills can hugely benefit gait analysis by minimizing startup costs and reducing the time required to collect data. However, it is imperative to recognize the limitations that exist in some models.

The University of Miami's Biomechanics Research Group Laboratory employs one of the leading models of instrumented treadmills on the market, the Kistler's Gaitway 9801A© Instrumented Treadmill. This treadmill is unique in its ability to measure F_z and center of pressure (CoP) for consecutive foot strikes during walking and running. The system uses a patented tandem force plate design and includes a patented algorithm which distinguishes left and right foot-strikes. Kistler's Gaitway 9801A© simplifies the challenges associated with force plate targeting that is common in overground walking. However, the treadmill is limited in its inability to measure F_{AP} and F_{ML}, which still require measurement using conventional force plate techniques.

The purpose of this study is to examine a method by which a treadmill was placed on four floor-mounted force plates; each of the four treadmill legs was centered on a floor-mounted force plate. Subjects walked overground at their normal speed across floor-mounted force plates. Data were collected which included walking speed and components of GRF. The subject then was asked to walk on the treadmill that is placed over the floor-mounted force plates. The treadmill speed was set to the subject's average speed collected during the overground walking trials. Force data were collected by the instrumented treadmill as well as by the four floor-mounted force plates. F_z was measured by both the instrumented treadmill and floor-mounted force plates. The floor-mounted force plates captured F_{AP} and F_{ML}. The the three components of GRF measured during a treadmill walk were compared with the three components of GRF measured during overground walking. Additionally, a regression approach was used to develop equations to associate Treadmill Ground Reaction Force Components with various measurements recorded during an overground walking trial.

Chapter 2
Literature Survey on GRF in Overground and Treadmill Walking

This chapter reviews literature on the measurement of GRF in overground and treadmill walking. Because significantly more research on this topic has been carried out since 2000, the chapter covers the period prior to 2000 separately from the period thereafter.

2.1 Research Prior to 2000

Many investigators presented data on GRFs during sprint running. In 1978, Payne reported data from a study conducted on a single runner (Payne 1978). F_z showed an initial peak of 5.5 BW at ground contact followed by a second peak of 3 BW in mid-support. F_{AP} exhibited clear double peaks during braking and a monophasic pattern during propulsion. Peak braking and propulsive forces were 0.8 BW and 0.6 BW, respectively. The F_{ML} component of 0.7 BW, directed both medially and laterally, was recorded.

That same year, Fukunaga et al. measured and reported two components of GRFs for sprinters (Fukunaga, Matsuo et al. 1978). The study was conducted using a single subject of unspecified body weight, and a force platform which had a first natural frequency of 109 Hz to record the forces for the sprinter who ran at a speed of 5.80 m/s, a speed of 7.43 m/s, and a speed of 9.03 m/s. The study presented three sets of curves for the vertical and the anterior-posterior components of GRF. The curves represent the three different speeds. The highest peak forces for both vertical and anterior-posterior components were recorded from the intermediate speed of 7.43 m/s. All three F_{AP} curves showed double peaks following foot strike. The first and second peaks of F_z were of similar magnitude during running at a speed of 5.80 m/s and a speed of 9.03 m/s. However, the first peak was substantially greater than the second when the sprinter was running at a speed of 7.43 m/s.

In 1980, van Ingen Schenau investigated the difference of opinion that exists about the mechanical equality of, or difference between, treadmill and overground locomotion (van Ingen Schenau 1980). Often the coordinate system which implicitly or explicitly is used in such locomotion study is the reason for the difference. With the help of a few theoretical examples of energy calculations, van Ingen Schenau showed that the description of treadmill locomotion with respect to a fixed coordinate system can lead to faulty conclusions. van Ingen Schenau further concluded that as long as belt speed is constant, a coordinate system should be used which moves with the belt. In such a system, no mechanical difference exists in comparison with overground locomotion with respect to a fixed coordinate system. All differences found in locomotion patterns must therefore originate from causes other than mechanical.

That same year, Cavanagh and Lafortune conducted a study to document the GRFs that occur during distance running, to examine the changes in the center of pressure (CoP) distribution of the human body throughout the support phase, and to obtain further insights into the changes in velocity of the body's center of mass (Cavanagh and Lafortune 1980). They documented that the foot placement angle of rearfoot strikers averaged 10.4°. CoP moved anteriorly to 50% of shoe length by 42 milliseconds, then remained within 50-80% until the end of support 146 milliseconds later. By contrast, midfoot strikers made contact at an average of 50% of shoe length, and CoP migrated posteriorly and medially after an initial but brief anterior movement. CoP reached its most posterior point at 20 milliseconds, followed by rapid anterior movement to 65% of shoe length in 40 millseconds.

In 1992, Hanke and Rogers investigated the reliability and validity of GRF measurements during dynamic transitions from bipedal to single-limb stance in healthy adults (Hanke and Rogers 1992). Since physical therapists routinely measure the movement performance of their patients, the research argues that methods used to assess patients and plan treatment protocols need to be justified with respect to reliability and validity, thus providing accurate information and minimizing misleading interpretations. Treatment protocols based on invalid or unreliable measurements may not adequately address underlying dysfunction, and they diminish therapeutic effectiveness.

Examination of the GRFs acting on a body during a standing leg flexion task further provided insights into the processes underlying the control of motion of the body. The study concluded that kinetic variables measuring the magnitude of the propulsion and braking phases of the linear momentum of the total body in the frontal plane are very consistent and demonstrate high reliability, regardless of speed of leg flexion movement. Also, kinetic variables related to temporal measures at natural speeds of movement are less consistent and exhibit low reliability.

Few studies have attempted to find the interacting causes that contribute to the development of overuse injury. As a consequence, GRFs during repetitive tasks, particularly running, have been investigated and a number of aspects of force exposure have been highlighted in the following studies:

Nigg et al. investigated overuse injury development including the magnitude of impact forces (Nigg, Denoth et al. 1981). Data from force platforms were used as one of the noninvasive methods to quantify the input signal for triceps surae soft tissue vibrations. The impact portion of the GRF is primarily due to the deceleration of the leg at landing. However, due to the influence of the effective body mass on the impact magnitude, the force plate data was inappropriate for quantifying a muscle tuning response.

Nilsson and Thorstensson investigated the variation in GRF parameters with respect to adaptations to speed and mode of progression, and to type of foot-strike (Nilsson and Thorstensson 1989). Six rearfoot strikers and six forefoot strikers subjects were studied walking at 1 – 3 m/s and running at 1.5 – 6 m/s. F_z, F_{AP} and F_{ML} components of GRF were recorded using a force platform and normalized to Body Weight (BW). The study found that F_z peak in walking and running increased with speed, F_{AP} peak amplitude and F_{ML} peak-to-peak time doubled with speed in walking and increased 2 – 4 times in running. Shorter support phase time was observed during the transition from walking to running. The study attributed the differences in the components of GRF between walking and running to “fundamental differences in motor strategies between the two major forms of human gait”.

Many studies contributed to the development of a framework for the cause-and-effect relationship between motion and injury by quantifying peak loads. Some of these studies were mentioned by Kuntze et al.; for example Nigg (Nigg 1983) investigated the rate of impact loading and Cavanagh and Lafortune (Cavanagh and Lafortune 1980) investigated the magnitude of the push-off force. Buczek and Cavanagh (Buczek and

Cavanagh 1990), Scott and Winter (Scott and Winter 1990), and Winter (Winter 1983) examined the magnitudes of loads at common injury sites and joint moments during running. "These studies provide insights into the functional significance of the joints of the lower limbs to the running gait, in particular the contribution of the knee and ankle."(Kuntze, Sellers et al. 2009)

In an attempt to investigate if treadmills could be used to simulate overground walking Nigg et al. studied twenty two subjects who ran overground and on treadmills of three different sizes and powers (Nigg, De Boer et al. 1995). It was found that the differences in the kinematics between treadmill and overground running could be divided into "systematic and subject-dependent components". "Subject systematically planted their feet in a flatter position more on the treadmill than overground". However the majority of the kinematic variables were not consistent among the subjects. These variables varied based on the subject's running style, running speed, and shoe/treadmill situation. As a result, "individual assessment of running kinematics on a treadmill for shoe or shoe orthotic assessment may possibly lead to inadequate conclusions about overground running".

Alton et al. investigated overground and treadmill walking for differences in gait temporal variables and leg joint kinematics (Alton, Baldey et al. 1998). In this study, seventeen healthy male and a female subjects were employed. All subjects walked overground at their chosen speed. The average speed from overground trials was used to set the treadmill trial. A 3D Kinemetrix Motion Analysis System was used to analyze gait temporal variables and leg joint kinematics. Data were analyzed separately for the two gender groups and for the two groups combined. The researchers found the following:

- In female subjects, maximum hip flexion angle was significantly different with greater flexion occurring on the treadmill.
- In male subjects, cadence and maximum knee flexion angle were significantly different with greater values in treadmill walking.
- When all subjects were compared, significant increases in hip range of motion, maximum hip flexion joint angle, and cadence during treadmill walking were observed along with significant decrease in stance time.

The researchers concluded that "statistically significant differences exist between overground and treadmill walking in healthy subjects for some joint kinematic and temporal variables."

Kram et al. constructed a force treadmill to measure and record vertical, horizontal and lateral components of the GRFs (F_z, F_y and F_x, respectively) and moments (M_z, M_y and M_x, respectively) exerted by walking and running humans (Kram, Griffin et al. 1998). The study used a custom-built, lightweight (90 kg), but mechanically-stiff treadmill which was supported along its length by a large, commercial force platform. The natural frequencies of vibration were well above the signal content of the GRFs. Numerous static and dynamic tests were performed to evaluate the validity of the constructed force treadmill. The researchers concluded that their device can accurately record F_z and F_y as well as the moments M_x and M_y. However, induced vibrations prevented satisfactory measurements of F_x and M_z.

The study conducted by White et al. aimed to compare F_z walking overground with vertical foot-belt forces for treadmill walking (White, Yack et al. 1998). In this study, 24 subjects were asked to walk overground and on a treadmill at slow, normal and fast speeds, and at similar cadences and stride lengths at each of the speeds. Force curves that were acquired during treadmill and overground walking were normalized to 100% of stance time, then compared using the subject's product moment correlation. ANOVA was used to compare measures from recorded vertical force between overground and treadmill locomotion. Post-hoc analysis consisted of paired t-tests with Bonferroni correction. All comparisons were made across conditions (treadmill vs. overground) at each of the three walking speeds.

The study found that the patterns of reaction forces were similar. The correlation between curves was 0.998, 0.983 and 0.983 for the slow (1.03-1.05 m/s), normal (1.40-1.44 m/s), and fast (1.65-1.71 m/s) walking trials. However, small but significant differences (5-9%) in force magnitude for the two forms of locomotion were detected during midstance for normal (p=0.00009) and fast (p=0.0007) walking speeds and in late stance for normal (p=0.0014) and fast (p=0.0005) trials. The researchers concluded that although the patterns of the vertical reaction forces for the two forms of locomotion were nearly identical," the interpretation of gait data collected on a treadmill should consider that forces during mid- and late-stance may be different than if the subject walked overground."

2.2 Research from 2000 to the Present

Rodano and Squadrone conducted a study to explain and examine a method and software they developed to perform a complete 3-D kinematic analysis in treadmill running (Rodano and Squadrone 2000). Eight recreational runners with average age of 28.7 ±4 years, average height of 174 ±4 cm, average body mass of 62 ±3 kg were asked to run on a treadmill at different speeds (2.78, 3.33, 3.89, 4.44 m/s) after a 15-minute warm-up period. Data was collected and analyzed using the researchers' developed procedure and software.

Kinematic data obtained showed the same significant differences in comparison with literature studies. The authors concluded that their method and software could be a useful tool for scientists, trainers and athletes to assess and evaluate biomechanical data during running. The authors highlighted the system's capability to collect simultaneously data from both sides of the body which is very useful in asymmetries characterizing runners.

Using static and dynamic tests, Belli et al. validated a newly designed treadmill ergometer which measures vertical and horizontal GRFs in the left and right legs during walking (Belli, Bui et al. 2001). The device shows promise in analyzing human gait. Nonlinearity ranged from 0.2% for F_z of the left leg, to 1.4% F_{AP} of the right leg. Resonance frequency ranged from 219 Hz in the right vertical direction to 58 Hz for the left medial/lateral direction. A calibration "leg" made from an air jack in series with a strain gauge generated measured force mean differences similar to the treadmill ergometer.

The purpose of the 2002 study by Li and Hamill was to examine the F_z component when transitioning from either walk to run or run to walk (Li and Hamill 2002). “The F_z of five steps before gait transitions for both walk-to-run and run-to-walk were collected on a motor driven treadmill with embedded force plates. Transition specific characteristics of F_z were observed for both types of gait transition. The study found that running peak force and time-to-peak force reduced dramatically in a quadratic fashion for run-to-walk transition. Also, the first peak of walking F_z increased linearly, and the second peak decreased.”

Examining variability in GRF patterns while walking at different constant speeds was the goal of a study conducted by Masani et al. (Masani, Kouzaki et al. 2002). They investigated whether or not the neuromuscular locomotor system is optimized at a unique speed. Ten healthy male subjects walked on a treadmill at 3.0, 4.0, 5.0, 6.0, 7.0, and 8.0 km/hr. F_z, F_y and F_x were measured for 35 consecutive steps for each leg. The investigators calculated coefficients of variation for first and second peaks of F_z, first and second peaks of F_y, and F_x peak to evaluate the GRF variability for each walking speed. The study concluded that,

> variability for the first and second peaks of F_z and the F_x peak increased in relation to increased increments in walking speed. However, there was a speed (5.5–5.8 km/hr) at which variability for first and second peaks of F_y—which are related to forward propulsion of the body—was at a minimum. This suggests that there is "an optimum speed" for the neuromuscular locomotor system but only with regard to the propulsion control mechanism.

Dierick et al. developed instrumented treadmill from a commercially available treadmill that was modified and fitted out with three-dimensional strain-gauge force transducers (Dierick, Penta et al. 2004). They tested the feasibility of using their developed device by measuring the ground reaction forces while healthy and patient subjects walked on the force measuring treadmill (FMT). Researchers concluded that the preliminary results of technical tests were satisfactory with an error less than 10% and dynamic tests in healthy subjects corresponded to the literature. The results of patients were clearly disturbed, demonstrating the ability of the FMT to discriminate pathological gaits from normal ones. However more work is needed to confirm their findings.

Forner Cordero et al. present and validate a method developed to calculate complete GRF components from the F_z measured using pressure insoles (Forner Cordero, Koopman et al. 2004). Insoles were equipped with pressure sensors to measure pressure distribution under the foot sole. The team measured several consecutive steps without any constraint on foot placement and computed a standard inverse dynamics analysis with an estimated GRF. Five healthy subjects participated in the study, walking three trials at their normal cadence. Motion and GRF data were recorded using a motion system (VICON 370, five cameras, 50 Hz), two force plates (AMTI force plates, 1000 Hz), and instrumented insoles (Pedar© at 50 Hz). The study claims that the only drawback to the proposed method is the error in the estimation of the horizontal GRFs which occur mainly at the beginning and end of the foot contacts.

In order to investigate the relationship between the peak values of F_z, Adelson et al. measured body weight equivalent force (F_z) and running economy (RE) during treadmill running (Adelson, Yaggie et al. 2005). RE is defined as the aerobic demand of submaximal running. The investigators assumed that changes at a given speed of running—whether mechanical, physical, environmental, or psychological—that lower oxygen consumption, and thus improve RE, should prove advantageous by allowing a faster pace with the same relative effect on the runner. Thirty five recreational runners of varying training background ran on a treadmill at 2.68 m/s (6 mi/hr) for eight minutes. RE and F_z were measured during the last two minutes of running. The study did not find any significant relationship between RE and F_z. However, a significant relationship was found between stride frequency (SF, in steps/minute) and RE; greater SF was indicative of better RE in treadmill running at 2.68 m/s.

Lake and Robinson compared walking kinematics in two shoe conditions in overground and treadmill walking (Lake and Robinson 2005). Ten healthy young females were asked to walk overground and on a treadmill in two footwear (a flat sandal and a training shoe). During overground testing, five walking trials at 1.25 m/s in each shoe condition across a force platform were recorded. The subjects also were asked to walk on a treadmill for 10 minutes at 1.25 m/s in each shoe condition. For overground testing, lower limb kinematics were captured by an 8-camera system at 240 Hz, and a force platform was used to record GRF. For treadmill testing, 6-camera 500 Hz motion was captured at one, five and nine minutes. Nine-millimeter reflective markers were placed on the medial and lateral tibial condyles, proximal and distal shaft of tibia, lateral tibia, medial malleolus, lateral malleolus, posterior, medial and lateral calcaneous, and the hallux. Results were compared between test methods.

The researchers observed that walking kinematics obtained using the overground and treadmill protocols were mostly similar. Data are alike in frontal and transverse plane ankle kinematics. Sagittal plane kinematics demonstrated some slight differences, however. When compared with overground data, treadmill data showed more significant differences in heel velocity at heel strike. Also, at heel strike the flat sandal showed no significant heel velocity differences for overground data collection but significant differences for mediolateral, horizontal and vertical velocity components during the treadmill protocol. There was a significant difference in the frontal plane ankle angle at toe off for treadmill data in comparison with overground data.

Veltnik et al. introduced a new method for continuous measurement of GRF using two force sensors with six degrees of freedom mounted under shoes in such a way that the foot can still be flexed during push-off, thus allowing normal gait (Veltink, Liedtke et al. 2005). According to the authors, the results demonstrate the feasibility of the proposed method.

Due to the anticipated increase in use of instrumented treadmills in gait evaluation Riley et al. conducted a study to show that measures of ground reaction force using instrumented treadmills are adequate for inverse dynamic analysis (Riley, Paolini et al. 2007). In addition researchers sought to well characterize the differences between treadmill and overground gait. Although all GRF maxima were found to be statistically significantly smaller in treadmill versus overground gait ($p < 0.05$), the magnitude of the differences was similar to the variability in normal gait parameter. The study concluded that “the mechanics of treadmill and overground gait are similar”.

In 2008, Goldberg et al. tested “the hypothesis that there would be no difference in the generation of anterior/posterior propulsion by performing a carefully controlled comparison of the F_{AP} and impulses in healthy adults during treadmill and overground walking” (Goldberg, Kautz et al. 2008). The study employed eight subjects who were asked to walk overground and on a treadmill, controlling both speed and cadence.

Less than 5% of BW reduction was observed in peak negative and positive horizontal GRFs in early and late stance during treadmill walking compared with overground walking. Also, the magnitude of the braking impulse was lower during treadmill walking. However, no significant difference was found between propulsion impulses. The study revealed slight but statistically significant differences in F_{AP} between overground and treadmill walking. Nevertheless, the researchers concluded that treadmill walking can be used to investigate propulsion generation.

Lee and Hidler compared treadmill walking with overground walking in healthy subjects who are free of any gait abnormality (Lee and Hidler 2008). Nineteen healthy subjects participated in the study by walking on a split-belt instrumented treadmill and then walking overground. Temporal gait parameters, leg kinematics, joint moments and powers, and muscle activity were used to compare treadmill walking to overground walking.

> Very few differences were found in temporal gait parameters or leg kinematics between treadmill and overground walking. Differences were detected in sagittal plane joint moments; in treadmill walking trials, subjects demonstrated less dorsoflexor moments, less knee extensor moments, and greater hip extensor moments. Joint powers in the sagittal plane were found to be similar at the ankle but different at the knee and hip joints. Some differences in muscle activities were observed between treadmill and overground walking—specifically with regard to tibialis anterior throughout stance, and in the hamstrings, vastus medialis and adductor longus during swing. It was concluded that although differences were observed in muscle activation patterns, and in joint moments and joint powers between the two walking modalities, the overall patterns of these behaviors were similar. Thus, from a therapeutic perspective, training individuals with neurological injuries on a treadmill appears to be justified.

O'Leary et al. attempted to determine the impact of cushioned insoles, if any, on running for healthy subjects (O'Leary, Vorpahl et al. 2008). This study involved 16 runners (nine females and seven males). The subjects ran five trials with and without soles. The data recorded in each trial included GRFs, tibial accelerations, lower-extremity kinematics, and subject-perceived comfort. As a result of cushioned insole, significant reduction in the following parameters were found:

- Mean vertical GRF peak impact (6.8%)
- GRF loading rate (8.3%)
- Peak tribial acceleration (15.8%)

Spectral analysis revealed no change in the predominant frequency or the power of the predominant frequency. The conclusion was reached that cushioned insole is effective in reducing peak impact force and tibial acceleration during running.

Riley et al. evaluated and compared kinematic and kinetic parameters for treadmill running and overground running (Riley, Dicharry et al. 2008). Twenty healthy young subjects were recruited and a motion capture system was used when subjects performed their overground trails. Each subject's average running speed was determined from the overground trials and was used to set the treadmill speed when the subjects ran on the instrumented treadmill. The study included results for 15 consecutive gait cycles and overground running (three cycles each limb). The authors concluded that kinematic and kinetic patterns were similar in treadmill gait to overground gait. Significant statistical differences were found in knee kinematics, peak values of the GRF, joint moment, and joint power trajectories. The study suggests that "parameters measured with and adequate treadmill are comparable but not directly equivalent to those measured for overground running." For instrumented treadmill measurements, a stiff treadmill surface and regulated belt speed is recommended.

Sohn et al. compared treadmill walking and overground walking at the same condition (Sohn, Hwang et al. 2009). The comparison was based on kinematics and energy expenditure. The study concluded that kinematics of treadmill and overground walking are similar. "The values at each joint were significantly different ($p<0.05$), but magnitude of the difference was generally less than 3°." The study also concluded that due to the increased stress during treadmill gait resulting from the continuous movement of the belt, energy expenditures are significantly greater than when measured overground.

Fellin et al. compared the variability of treadmill and overground running through a 3D, lower limb kinematic analysis (Fellin, Manal et al. 2010). The researchers tested the hypothesis that lower limb hip, knee and rearfoot angles would exhibit decreased variability during treadmill running compared to overground running. The study recruited 20 subjects (25.2 ± 6.2 yrs) of both genders who are rearfoot strikers, run at least 10 miles each week, and were familiar with treadmill running. Reflective markers were used for the right lower extremity of each subject. Subjects ran overground on a 25 meter runway and on a treadmill. The order of overground and treadmill running was counterbalanced. Speed was monitored by photocells, and trials of 3.35 m/s ±5% were accepted. The results indicated that, for initial contact, subjects exhibited smaller standard deviations during treadmill running for seven of nine joint angles. For peak angles, treadmill running exhibited smaller standard deviation for eight of the nine angles. Fifteen out of eighteen measures for lower limb, 3D kinematic variables supported the proposed hypothesis. (Refer to Table 2.1.) The largest difference was found for frontal plane rearfoot position at initial contact.

Condition	Joint	Sagittal			Frontal			Transverse		
		TM SD	OG SD	Diff	TM SD	OG SD	Diff	TM SD	OG SD	Diff
Initial Contact	Hip	1.15	1.40	**-0.26**	1.22	1.30	**-0.08**	1.17	1.19	**-0.02**
	Knee	1.58	1.77	**0.19**	0.54	0.46	**0.08**	1.18	1.40	**-0.22**
	Rearfoot	1.80	1.95	**-0.15**	1.37	1.82	**-0.45**	1.57	1.52	**-0.04**
Peak	Hip	1.25	1.51	**-0.27**	1.05	1.34	**-0.30**	0.99	0.99	**0.00**
	Knee	1.13	1.36	**-0.24**	0.54	0.57	**-0.03**	0.83	1.06	**-0.23**
	Rearfoot	1.18	1.41	**-0.23**	0.78	0.95	**-0.17**	1.08	1.27	**-0.20**

Table 2.1 Group mean standard deviations for treadmill and overground running. Differences are the average of the individual differences between conditions. Negative differences indicate treadmill SD is less than overground SD. All units are in degrees.

Zeni and Higginson conducted a study using a split-belt treadmill with dual force plates to find out which gait variables are altered when initially walking on the treadmill (Zeni and Higginson 2010). Changes in these gait variables over a longer period of treadmill walking were also examined. Nine healthy subjects at average age of 24.1 years old were asked to walk on the treadmill for nine minutes at a comfortable walking speed of 1.25 or 1.30 m/s. Kinematic and kinetic data were recorded. However data was recorded from the first thirty seconds of each minute. Force data were collected using two force plates integrated into the treadmill. Additionally a motion capture system was utilized. A paired t-test was used to determine "differences between step width, step length variance and GRFs between trials." The study found significant reduction in step width and a reduction in the variability of step length the longer the subjects walked on the treadmill. No significant differences were found in step length, vertical, posterior GRF, or knee flexion at heel strike for each subject throughout the nine minutes. As a result, the authors suggest familiarizing subjects to treadmill walking for at least four to five minutes before capturing data.

The control of the GRFV relative to the center of gravity (CoG) was examined by Toussaint et al. while subjects performed a back-lifting task (Toussaint, Commissaris et al. 1995). Six male subjects (aged 24.0 +/- 2.5 years) repeatedly lifted a barbell. A biomechanical analysis that used a linked segment model revealed that the summed rotations of body segments during lifting yielded a specific rate of change of the angular momentum of the entire body. This equaled the external moment provided by the gravitational force relative to CoG. This implies that multisegment movements involve control of the angular momentum of the entire body through an appropriately directed gravitational force. Thus, in dynamic tasks gravitational force is pointed away from rather than lined up with the CoG, as is the case in static tasks.

In addition, several studies have been conducted utilizing GRF in movement recognition. For example, Headon and Curwen introduced a classification system to recognize common, everyday primitive human movements such as taking a step, jumping, drop-landing, sitting down, rising to stand, and crouching (Headon and Curwen 2001).

Correlation between peak F_z, as measured by a force plate, and tibial axial accelerations during free vertical jumping was studied by Elvin et al. (Elvin, Elvin et al. 2007). The investigators determined that inobtrusive accelerometers can be used to determine the GRF experienced in a jump landing. Whereas the devices also permitted an accurate determination of jump height, there was no correlation between peak GRF and jump height.

In conclusion, literature on the topic of GRF in overground and in treadmill locomotion was reviewed in this chapter. The selection of papers addressed the following areas:

- The assessment of GRF during overground walking, jogging or running.
- The assessment of GRF during treadmill walking, jogging or running.
- The validation of GRF readings obtained from instrumented treadmills.

Chapter 3
Methods and Procedures

3.1 Subjects

Subjects were recruited among students from the College of Engineering at the University of Miami. Volunteers for the study completed a questionnaire (included as Appendix A) regarding their gender, age, height, weight, left- or right-handedness, history of musculoskeletal injuries, and availability. Twelve right-handed males with no history of musculoskeletal injuries were selected. All participants were briefed in advance about the purpose and experimental procedure of the study, and each signed a written consent form before beginning.

The subjects' age, height, and weight were (Mean ± Standard Deviation) 20.6 ± 5.2years, 176.53 ± 10.17cm, and 81.08 ± 17.28 kg, respectively. Table 3.1 details the demographic data for the subjects.

Subject No.	Age (years)	Height (cm)	Weight (kg)	Average Walking Speed (km/hr)
1	19	180.3	72.6	4.5
2	37	165.7	86.6	3.4
3	20	190.5	98.9	3.1
4	19	185.4	82.8	3.2
5	18	165.1	61.7	2.7
6	20	171.5	69.2	3.7
7	18	166.4	55.3	4.2
8	20	165.1	74.4	2.9
9	18	183.5	78.9	3.0
10	20	193.0	120.7	3.4
11	19	179.1	83.0	4.0
12	19	172.7	88.9	3.8

Table3.1 Demographic Data of Participating Subjects

3.2 System

3.2.1 Force Plates

In this study, Kistler force plates were used. Each plate is multicomponent since it measures GRFs, moments, and CoP. These devices consist of a top plate with four, 3-component piezoelectric force sensors that output an electric charge strictly proportional to the applied force. Quartz is used as part of the piezoelectric sensors because of its long-term stability, high rigidity strength, and wide measuring ranges. The quartz washers come in different sizes adaptable to different measuring ranges. Quartz sensitivity is measured in pC/N (picoCoulomb per Newton). Short-term static pressure measurements are more feasible with quartz than with any other piezoelectric material due to its high insulation resistance. The output of these sensors is internally combined into eight channels for force and torque measurements in x-, y- and z-axes. The CoP and torque, normal to the plate, can be calculated using a Kistler Data Sheet.

Figure 3.1. Kistler Force Plate – Type 9287BA

UM's Biomechanics Lab has four Kistler force plates: three Type 9281CA 60x40 centimeters, and one Type 9287BA 90x60 centimeters (Figure 3.1). The lab allows for several force plate combinations so they can accommodate different experimental designs. Figure 3.2 shows the two arrangements of the force plates for this study: Configuration A and Configuration B.

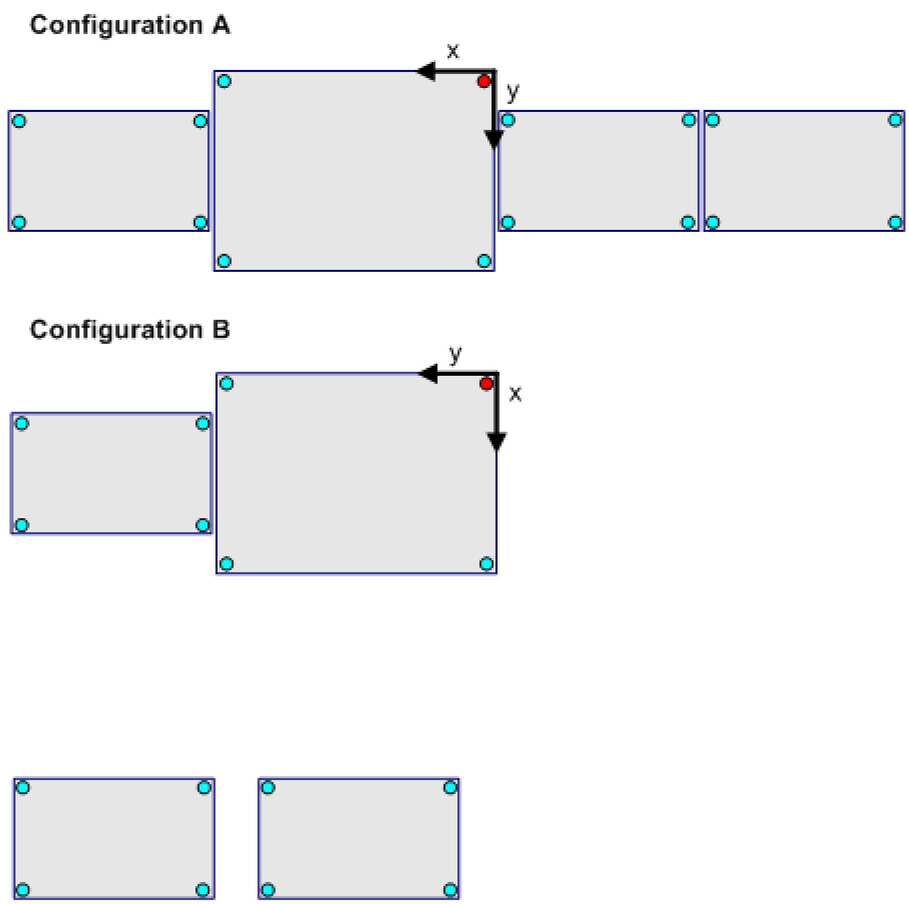


Figure 3.2. The two force plate arrangements used in this study
(Configurations A and B).
The direction of locomotion is along the x-axis.

The Biomechanics Lab utilizes a motion analysis technology by Oxford Metrics called Vicon Motion Capture System. It supports 64 channels of analog data and integrates and synchronizes eight infrared cameras, using the four force plates for complete control and analysis of motion captured. In this study, the Vicon Motion Capture System was utilized to obtain GRFs from the force plates.

3.2.2 Treadmill

The Biomechanics Lab owns a Kistler's Gaitway© Instrumented Treadmill, Type 9810AS10 (Figure 3.3) that was utilized in this study. The treadmill is a gait analysis system housed in a commercially manufactured treadmill. It measures F_z and CoP for complete consecutive foot strikes during walking and running. The treadmill uses a patented tandem force plate design and a patented algorithm to distinguish left and right foot strikes. The Gaitway treadmill offers the ability to vary cadence, speed and grade. It can be programmed for speeds 0.1 km/hr to 22 km/hr, and grade 0 to 24%. The treadmill is accompanied by Gaitway software (ver. 2.06, build 2013) which collects data from the treadmill and quickly produces a gait report with more than 25 gait parameters. However, in this study the Gaitway software was used only to distinguish the dominant foot strike of each subject.

Figure 3.3. Kistler Gaitway Instrumented Treadmill Type 9810AS10

3.3 Experimental Procedure

Twelve right-handed male subjects ages 18 to 37 were selected. A subject's order of participation was based solely on their availability. At the Biomechanics Lab, subjects were questioned if they had suffered any prior musculoskeletal injuries, in particular if they had suffered any injuries in the lower extremities, or if they had any health problems that would affect their gait. In order to avoid additional variability in the data, only right-handed males free of any musculoskeletal injuries or problems affecting gait were selected. Two appointments were issued for each subject, the first appointment to perform the overground walking experiment, and the second to perform the treadmill walking experiment.

3.3.1 Overground Walking

The goal of each subject's first visit to the Biomechanics Lab was to measure overground walking. Subjects were briefed about the procedure and presented with a written consent form to sign. Height and weight were measured using a physician's scale. Subjects were then asked to walk barefooted through the room at their comfortable (normal) walking speed over force plates set up as Configuration A. To calculate walking speed, the time from start to end was measured using a stopwatch (refer to Figure 3.4). Resetting the force plates before each trial, up to ten trials were collected per subject. However, only six randomly selected good trials were used in data analysis (a trial is considered "good" if the subject did not target the force plates and landed only one foot strike per force plate). Average walking speed for each subject was calculated using the time recorded from the six selected trials.

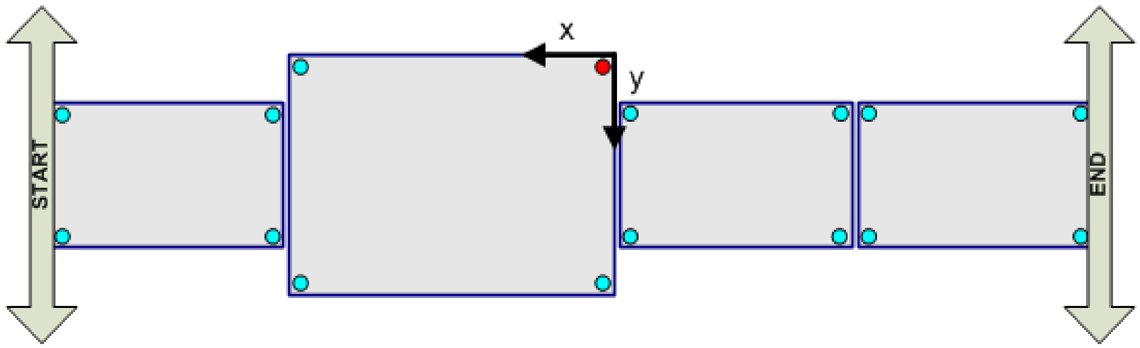


Figure 3.4. Configuration A: Force plate arrangement for overground walking.

3.3.2 Treadmill Walking

Before a subject's second visit to the Biomechanics Lab, the force plates were rearranged to Configuration B (Figure 3.2). The Kistler's Gaitway Instrumented Treadmill was placed on top of the floor-mounted force plates such that each of the treadmill's legs was centered on a single force plate (illustrated in Figure 3.5).

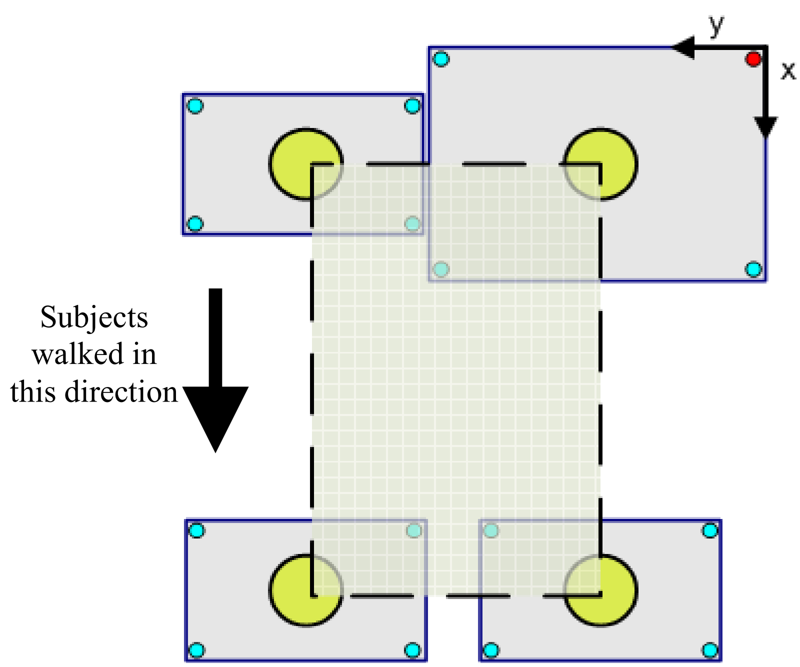


Figure 3.5. Treadmill and force plate position for treadmill walking.

Subjects were asked to practice walking on the treadmill barefooted. When the subject felt comfortable enough, his weight was measured using the treadmill's built-in feature, and the treadmill's speed was set to the subject's average walking speed. (The subject's average walking speed had been measured during the subject's first visit.) Data was then collected from the floor-mounted force plates for a complete gait cycle. Data was recorded using Gaitway software and the Vicon Motion Capture System.

3.4 Experimental Design and Statistical Analysis

The aim of this study is to uncover statistically significant differences in GRF components (i.e., F_z, F_{AP}, F_{ML}) between overground walking and walking on a treadmill placed on top of floor-mounted force plates. Twelve right-handed males in the age range of 18–37 years participated. Subjects with prior musculoskeletal injuries or asymmetrical gait as well as subjects with osteoarthritis were excluded. The experimental design includes walk type as a factor: overground walking vs. treadmill walking. For each subject, six overground walking trials for the dominant side (all subjects were right-handed) and one treadmill walking trial for the dominant side were recorded. A total of 84 trials were analyzed for this study.

Dependents (response) variables:

- Vertical Ground Reaction Force (F_z) Peak1, Peak2 and Peak3 (VGRFP1, VGRFP2 and VGRFP3, respectively)
- Anterior-Posterior Ground Reaction Force (F_{AP}) Peak1 and Peak2 (APGRFP1 and APGRFP2, respectively)
- Medial-Lateral Ground Reaction Force (F_{ML}) Peak1 and Peak2 (MLGRFP1 and MLGRFP2, respectively)

Several graphs were generated to uncover trends in the data and determine appropriate statistical tests to use to analyze the data. A plot for each response variable was created showing the subject number on the x-axis and the six overground walking measurements as well as the treadmill walking measurement on the y-axis. Additionally, pair-wise scatterplots of response variables were generated to assess how they correlate with the overground walking measurements as well as with the treadmill walking measurements.

Preliminary analysis of the obtained measurements was simple: values obtained from the six overground trials for each subject were averaged for each response variable and compared to those obtained from treadmill walking using a paired test. To choose the appropriate paired test, normal probability plots were examined to check for normality. Since the data did not appear normally distributed, a nonparametric test (the Wilcoxin signed rank test) was used instead of a paired t-test. However, by assuming the data were normally or close to normally distributed, a more involved General Linear Model for Repeated Measures further assessed the difference between each overground measurement to each treadmill measurement. This model takes into account all six of the overground measurements as well as intersubject variability.

The software programs used to perform the statistical analysis for this experiment are SAS 9.2, Minitab 15 & 16 and MS Excel 2010. Results of the above tests are detailed and discussed in the following chapters.

Chapter 4
Results

4.1 Preliminary analysis

Data were plotted in graphical form which is a powerful tool for deducing and understanding general trends. Graphs also serve as exploratory tools in the process of fitting a model to data (Chatterjee and Hadi 2006). For each response variable, a plot was created showing twelve subjects along the x-axis with walks performed by each subject on the y-axis (six overground walks and one treadmill walk per subject). The results are presented below in Figures 4.1 through 4.7.

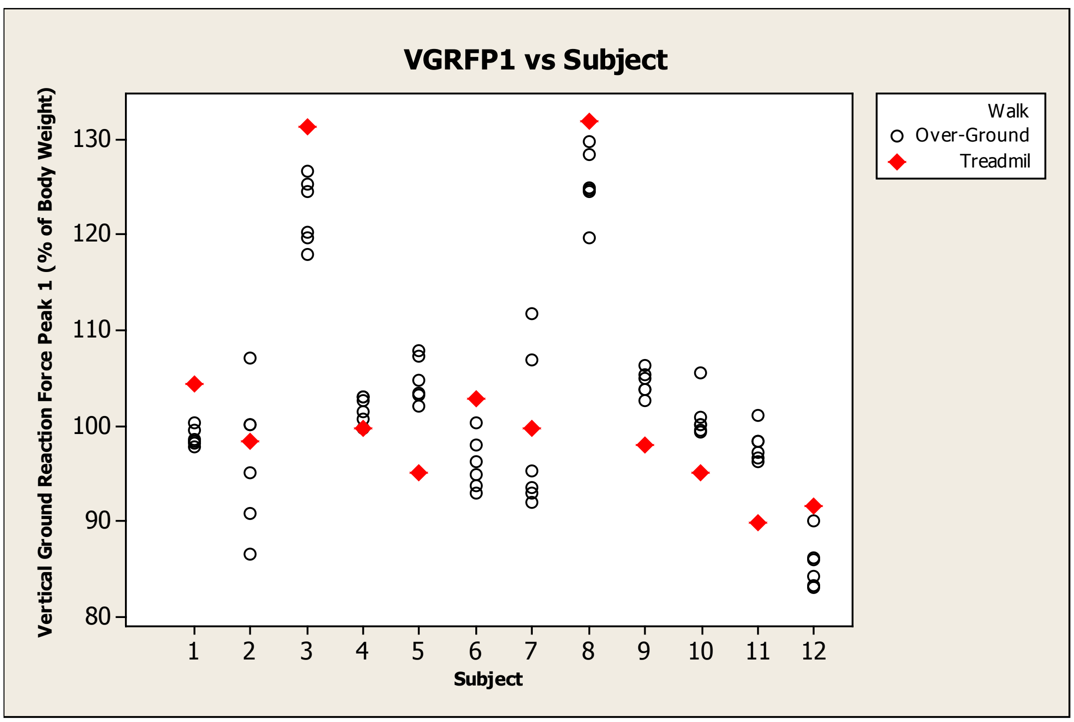


Figure 4.1 Vertical GRF (F_z) Peak1 measurements for each subject.

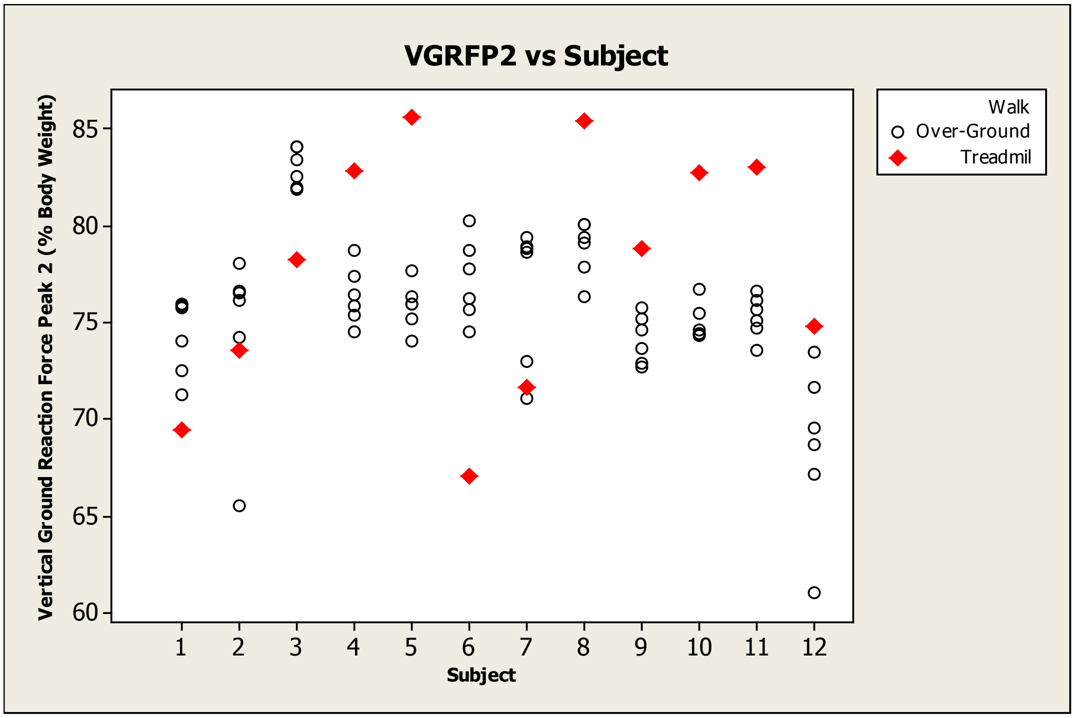


Figure 4.2 Vertical GRF (F_z) Peak2 measurements for each subject.

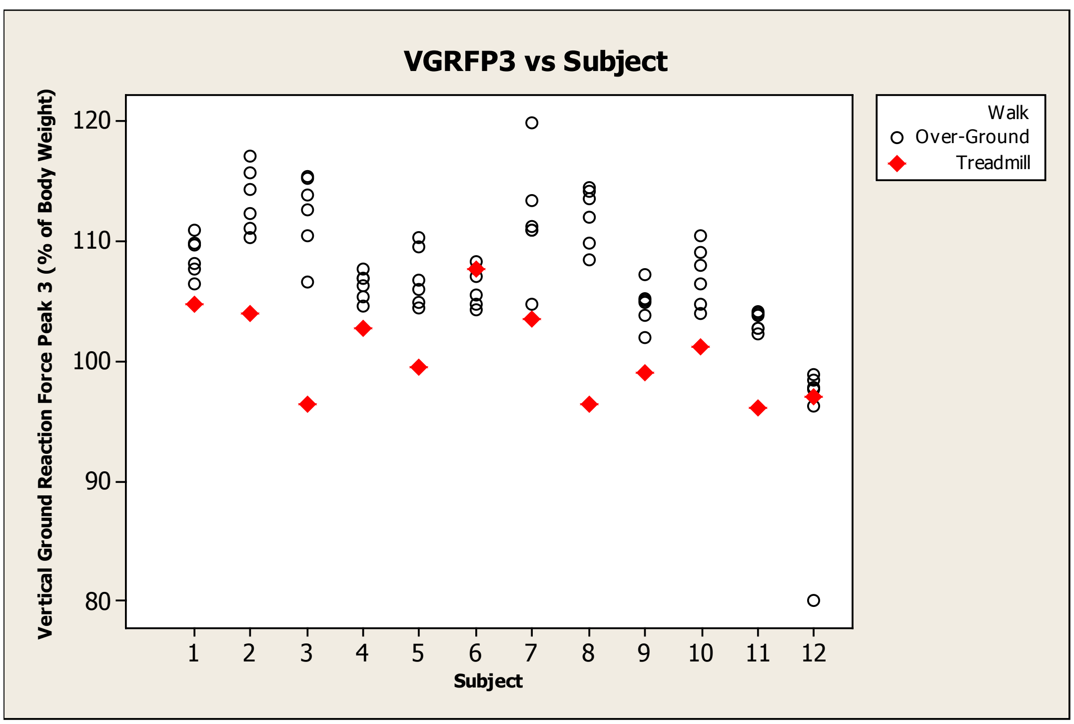


Figure 4.3 Vertical GRF (F_z) Peak3 measurements for each subject.

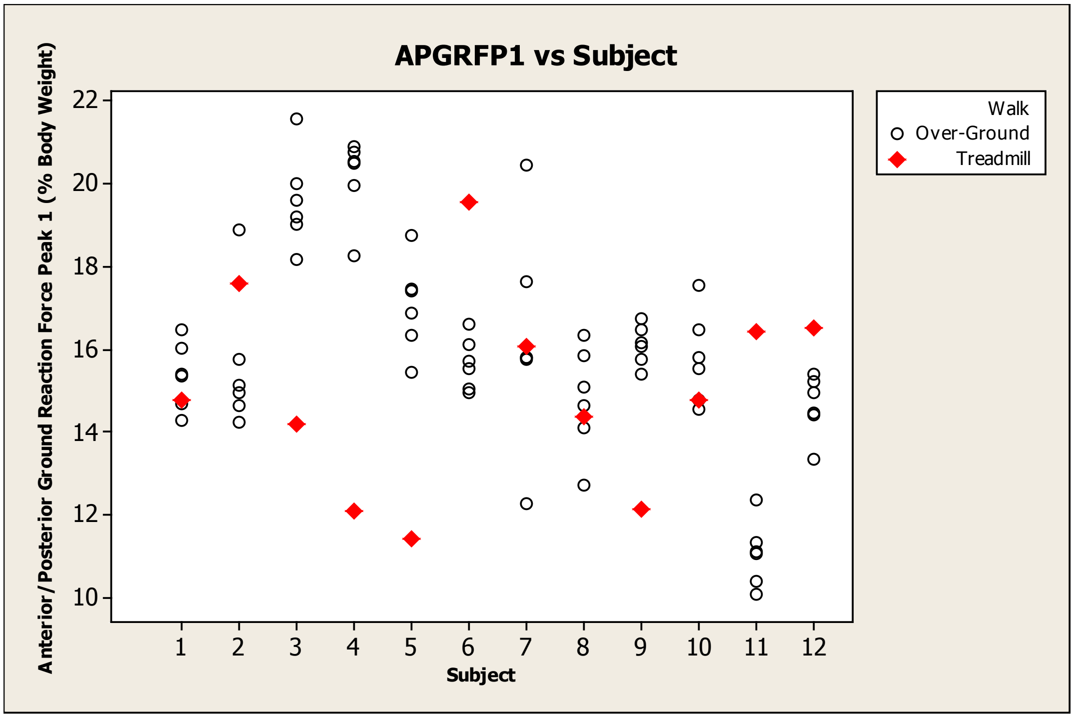


Figure 4.4 Anterior/posterior GRF (F_{AP}) Peak1 measurements for each subject.

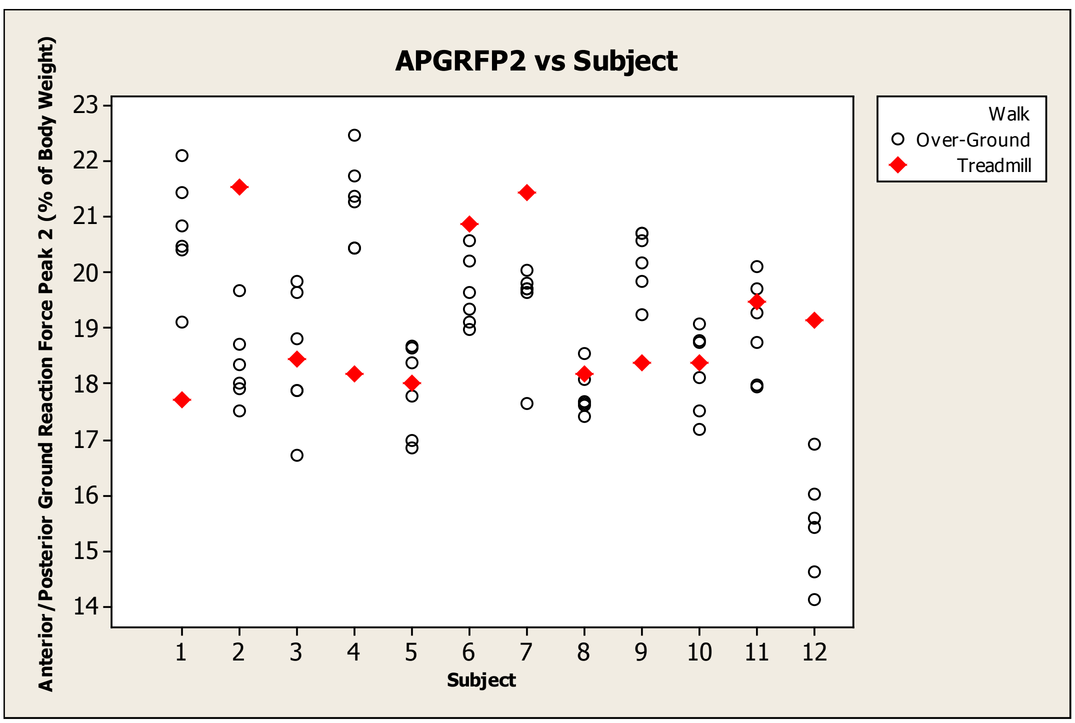


Figure 4.5 Anterior/posterior GRF (F_{AP}) Peak2 measurements for each subject.

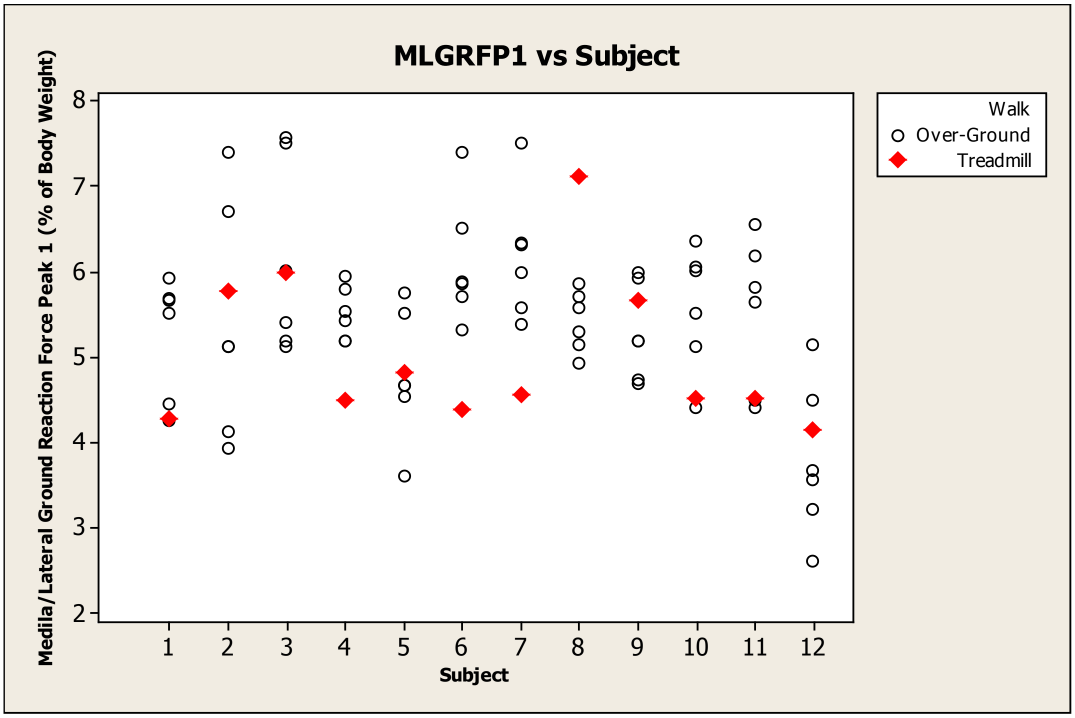


Figure 4.6 Medial/lateral GRF (F_{ML}) Peak1 measurements for each subject.

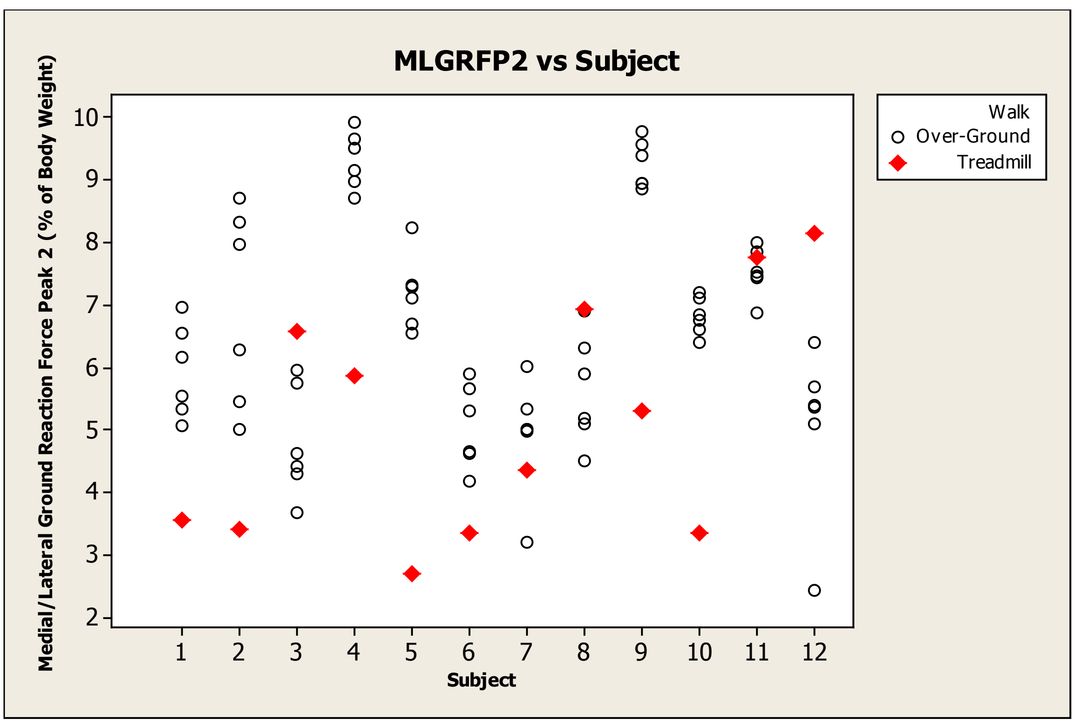


Figure 4.7 Medial/lateral GRF (F_{ML}) Peak2 measurements for each subject.

In addition, pairwise scatter plots were generated to study the correlation between walks for each response variable. These plots are presented in Figures 4.8 through 4.14

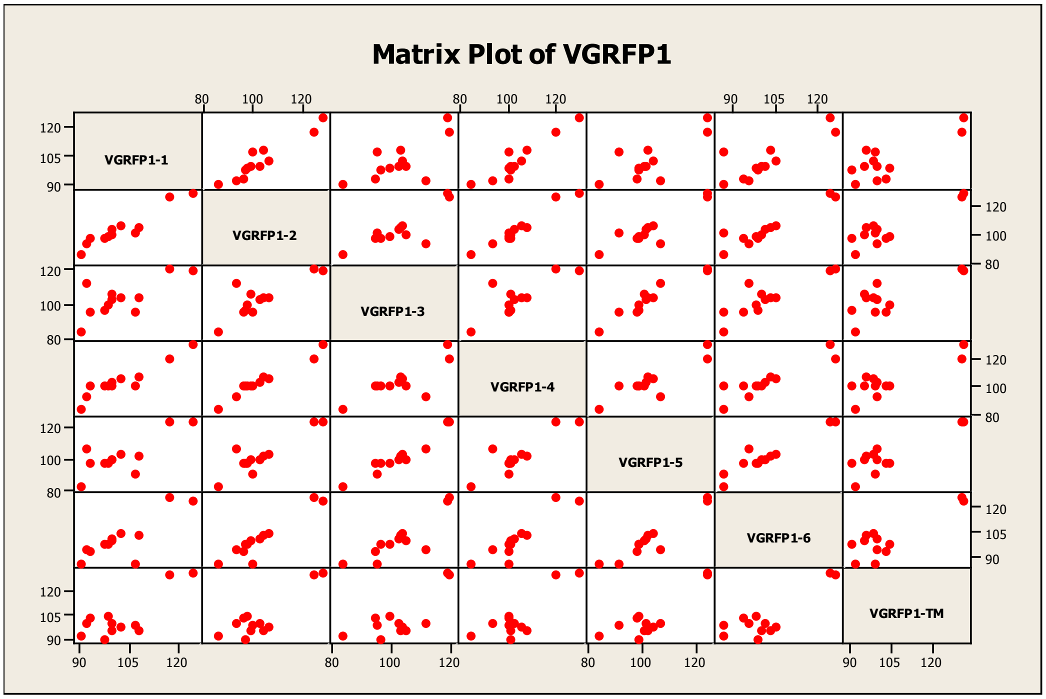


Figure 4.8 Correlations between trials for the vertical GRF (F_z) Peak1.

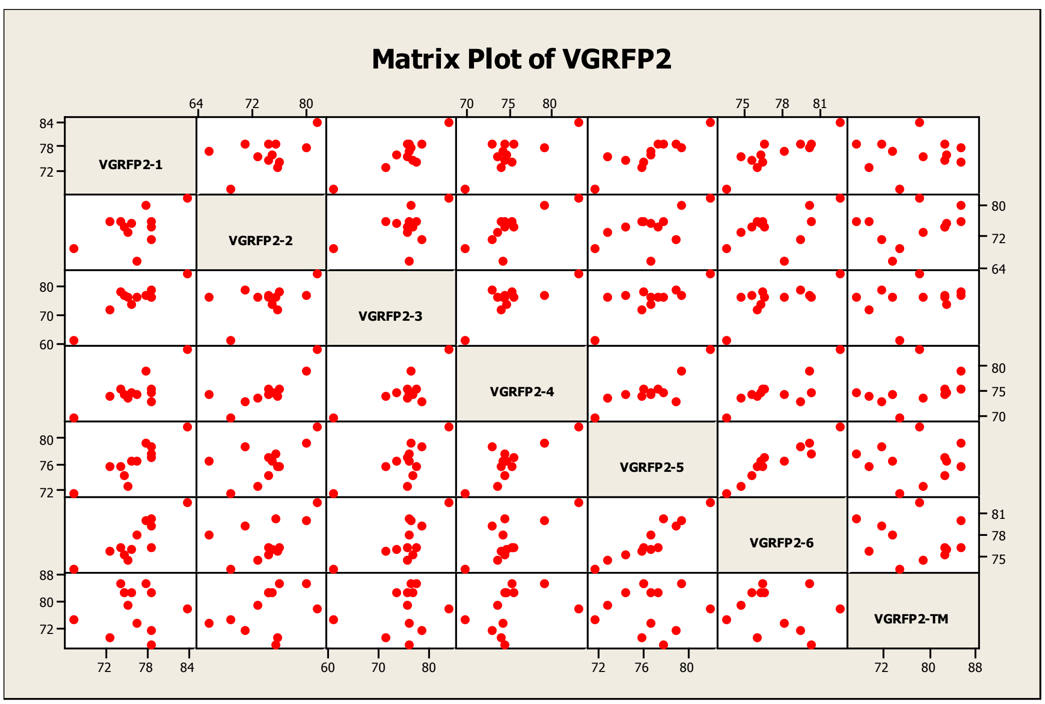


Figure 4.9 Correlations between trials for the vertical GRF (F_z) Peak 2.

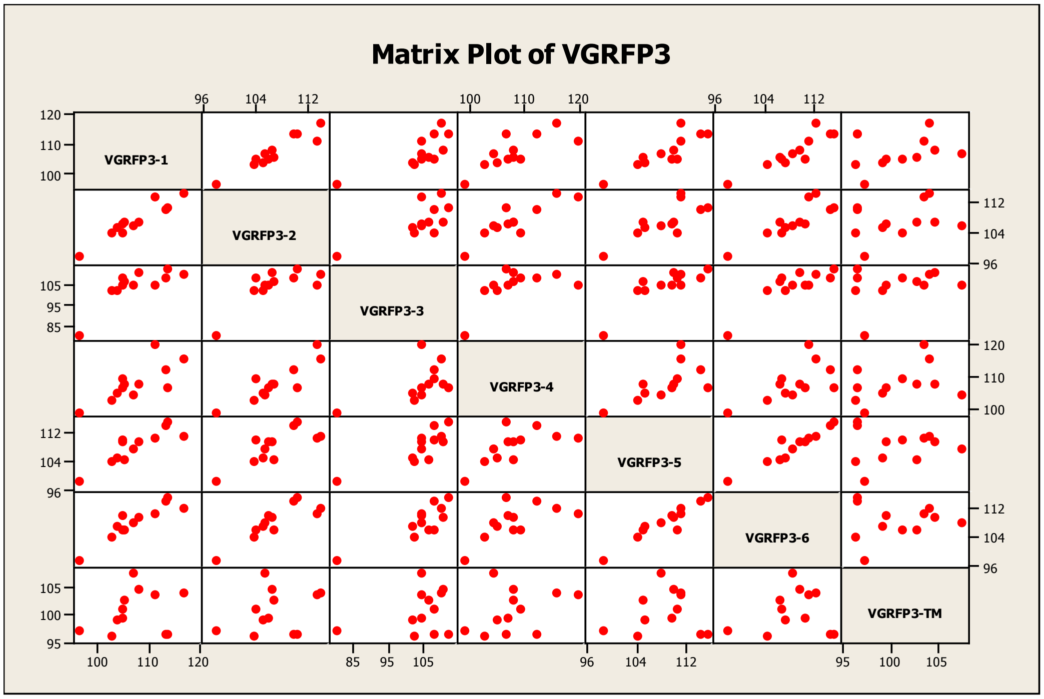


Figure 4.10 Correlations between trials for the vertical GRF (F_z) Peak3.

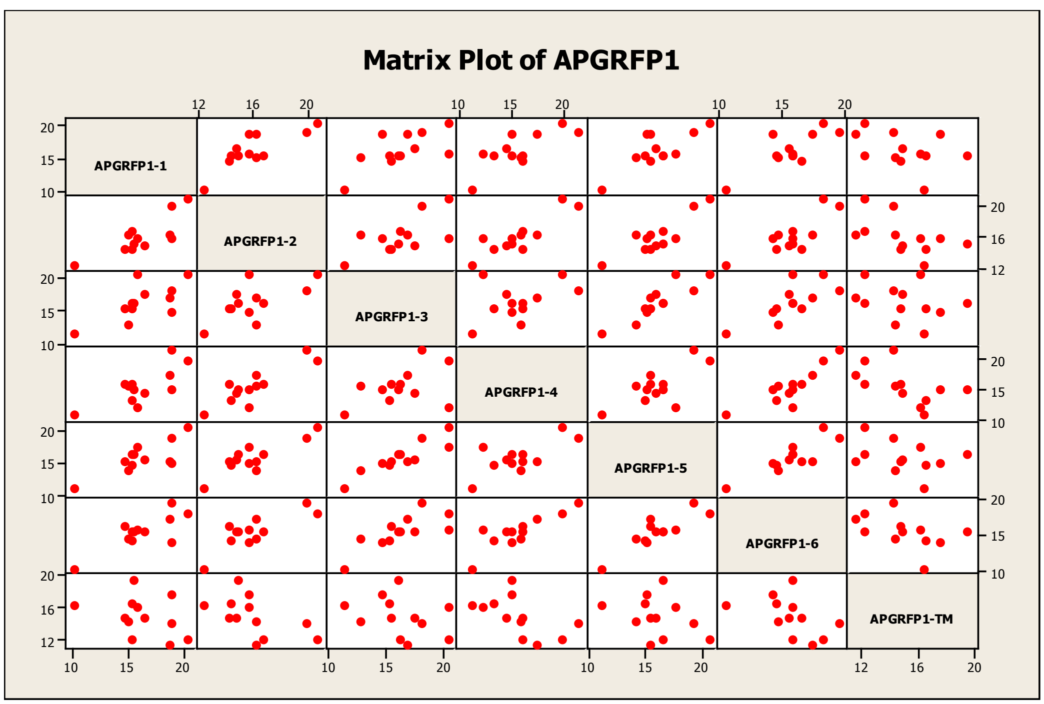


Figure 4.11 Correlations between trials for the anterior/posterior GRF (F_{AP}) Peak1.

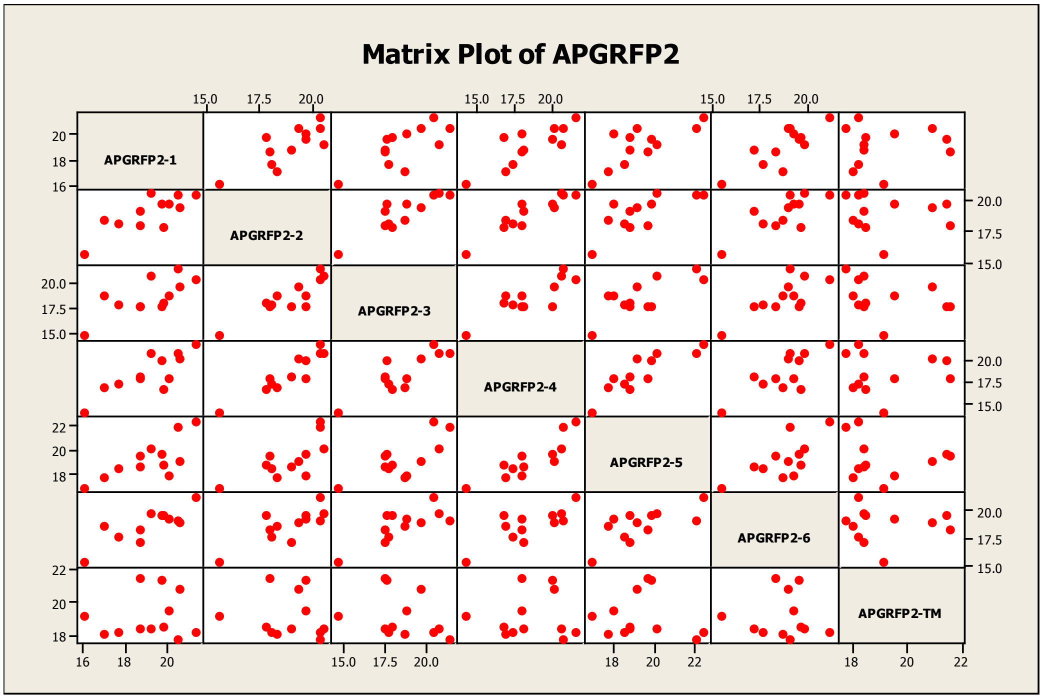


Figure 4.12 Correlations between trials for the anterior/posterior GRF (F_{AP}) Peak2.

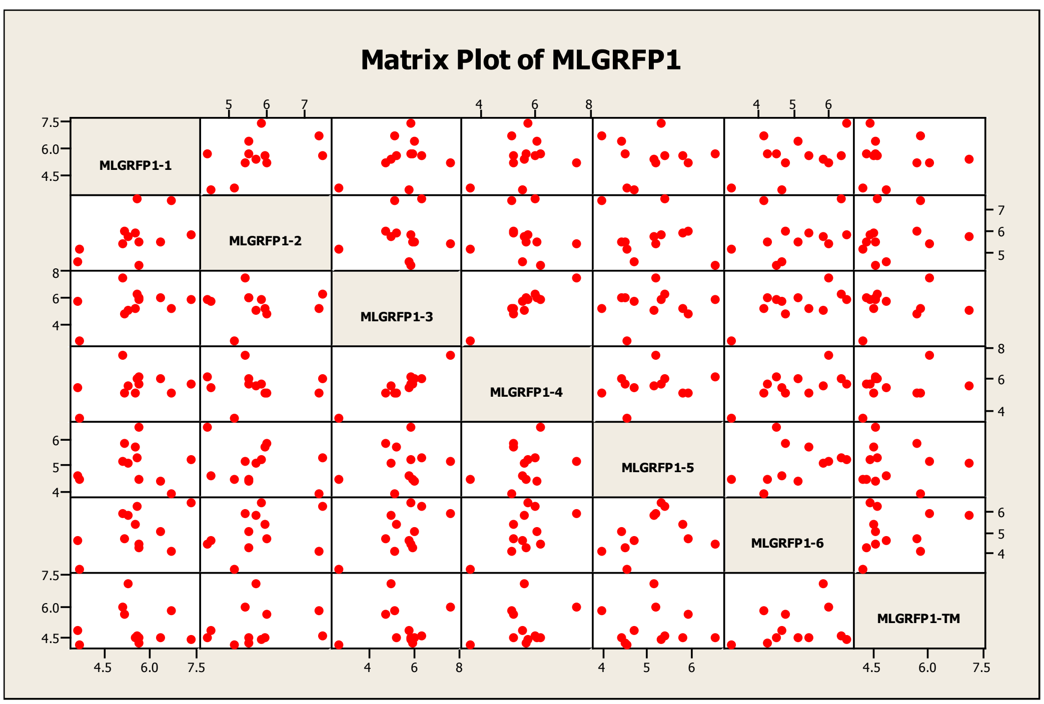


Figure 4.13 Correlations between trials for the medial/lateral GRF (F_{ML}) Peak1.

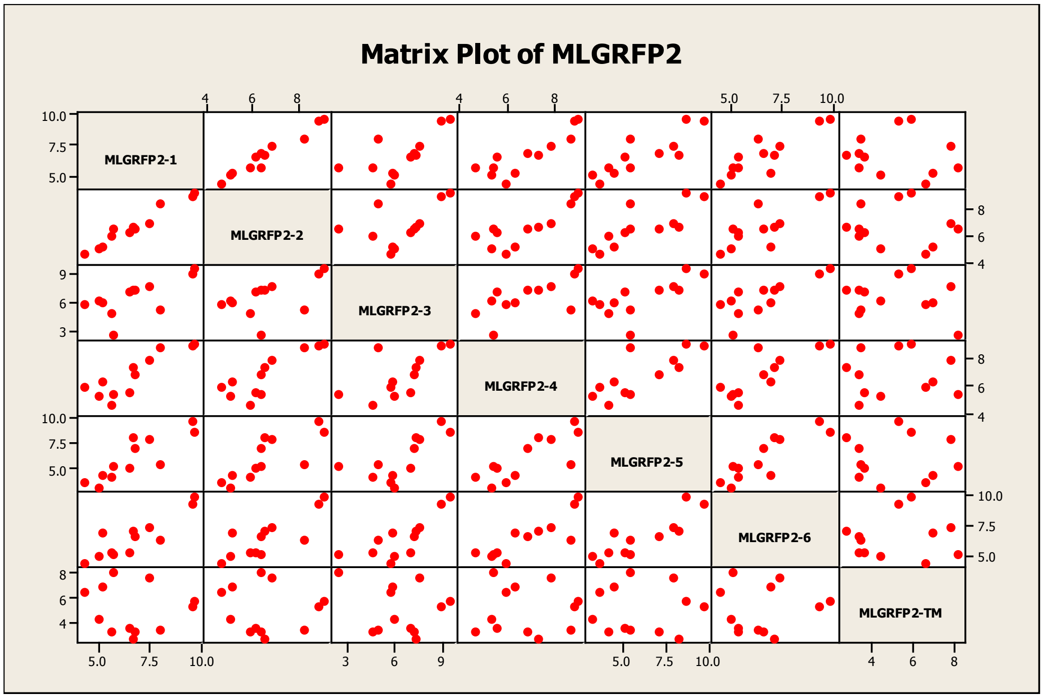


Figure 4.14 Correlations between trials for the medial/lateral GRF (F_{ML}) Peak2.

4.2 Normality Tests

Many statistical procedures require the response variables (GRFs in this study) being analyzed to have a normal distribution around the mean. It is a technique which indicates whether or not correct statistical procedures are being utilized. The Shapiro-Wilks W Test is the standard test for normality and is recommended for small samples. Table 4.1 summarizes the results obtained for the Shapiro-Wilks W test.

Response Variable	Test Statistics[a]
AvgOG[b]_VGRFP1	p = 0.0423*
TM[c]_VGRFP1	p = 0.0023*
AvgOG_VGRFP2	p = 0.2287
TM_VGRFP2	p = 0.3372
AvgOG_VGRFP3	p = 0.1220**
TM_VGRFP3	p = 0.3072
AvgOG_APGRFP1	p = 0.1786
TM_APGRFP1	p = 0.8147
AvgOG_APGRFP2	p = 0.7307
TM_APGRFP2	p = 0.0167*
AvgOG_MLGRFP1	p = 0.556
TM_MLGRFP1	p = 0.0178*
AvgOG_MLGRFP2	p = 0.1178**
TM_MLGRFP2	p = 0.1884
a Shapiro-Wilks W Normality Test b AvgOG: Average of the 6 overground walks c TM: Treadmill Walk * Significant at p=0.05 ** Close to being significant at p=0.10	

Table 4.1 Results of Shapiro-Wilks W Normality Test.

The results of the Shapiro-Wilks W test for normality indicate that data in some of the response variables do not follow a normal distribution.

4.3 The Wilcoxon Signed Rank Test for Simple Association

The Wilcoxon Signed Rank Test is a nonparametric paired difference test used when comparing two sets of measurements to assess if their population means differ. The Wilcoxon Signed Rank Test was performed with the mean of the six overground walk measurements compared with the treadmill walk measurement, for each of the seven response variables of each of the twelve subjects. Results are presented in Table 4.2.

Response Variable	Test Statistics[a]
VGRFP1	p = 0.9697
VGRFP2	p = 0.3013
VGRFP3	p = 0.0024*
APGRFP1	p = 0.3804
APGRFP2	p = 0.3804
MLGRFP1	p = 0.2661
MLGRFP2	p = 0.0771**
a Wilcoxon Signed Ranks Test * Significant at p = 0.05 ** Significant at p = 0.10	

Table 4.2 Results of Wilcoxon Signed Ranks Test.

From the above results at the p=0.05 level, the Wilcoxon Signed Rank test suggests that the third peak of F_z significantly differs between the treadmill walk and the average of the overground walks. Also, at the p=0.10 level, the second peak of F_{ML} significantly differs between the treadmill walking measurement and the average of the overground walking measurements. The test did not detect any significant differences between treadmill walking and average overground walking in the first and second peaks of F_z, in the first and second peaks of F_{AP}, or in the first peak of F_{ML}.

4.4 General Linear Model (GLM) with Repeated Measures

GLM Repeated Measures is a procedure used to model dependent variables measured at multiple times using analysis of variance. It tests the main effects on repeated measures of between-subjects (grouping) factors, the main effects of within-subjects factors such as measurement times, interaction effects between factors, covariate effects, and effects of interactions between covariates and between-subjects factors. The following table summarizes the results obtained from the GLM for repeated measures analysis covered here.

Response Variable	Walk Type	Subject*Walk Interaction
VGRFP1	p = 0.780	p = 0.013*
VGRFP2	p = 0.061**	p = 0.000*
VGRFP3	p = 0.000*	p = 0.010*
APGRFP1	p = 0.090**	p = 0.000*
APGRFP2	p = 0.418	p = 0.000*
MLGRFP1	p = 0.139	p = 0.245
MLGRFP2	p = 0.000*	p = 0.000*
* Significant at p=0.05 ** Significant at p=0.10		

Table 4.3 Results obtained from GLM with repeated measures.

The GLM for repeated measures suggests that at p=0.05, the third peak of F_z and the second peak of F_{ML} significantly differ between treadmill walking and overground walking. At a higher p value, the analysis suggests that the second peak of F_z and the first peak of F_{AP} also significantly differ between treadmill walking and overground walking. In addition, the analysis reveals that the interaction between subjects and each walk (Subject*Walk) is statistically significant for all response variables except for the first peak of F_{ML}. Because further insight into this interaction was needed, Main Effects Plots and Interaction Plots were generated to be analyzed alongside Scatterplots of response variable versus subject. In these plots, Walk 1 represents the average of six overground walks while Walk 2 represents one treadmill walk. The goal was to investigate whether or not the presence of the subject-walk interaction influenced results.

VGRFP1

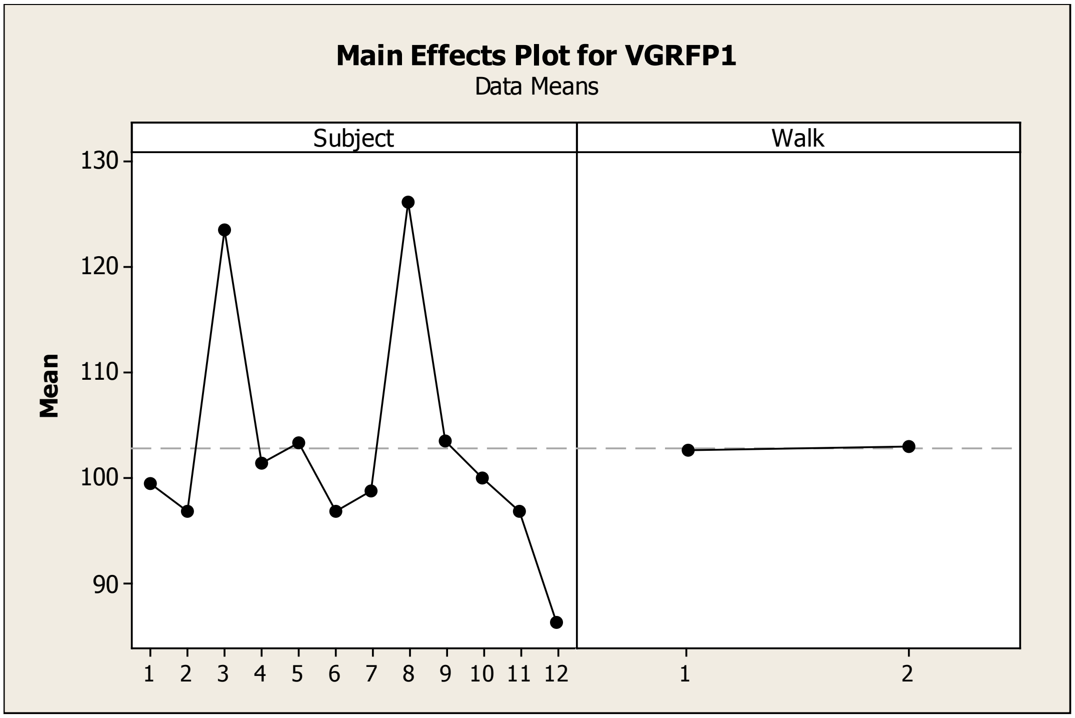


Figure 4.15 Main Effects Plot for vertical GRF (F_z) Peak1.

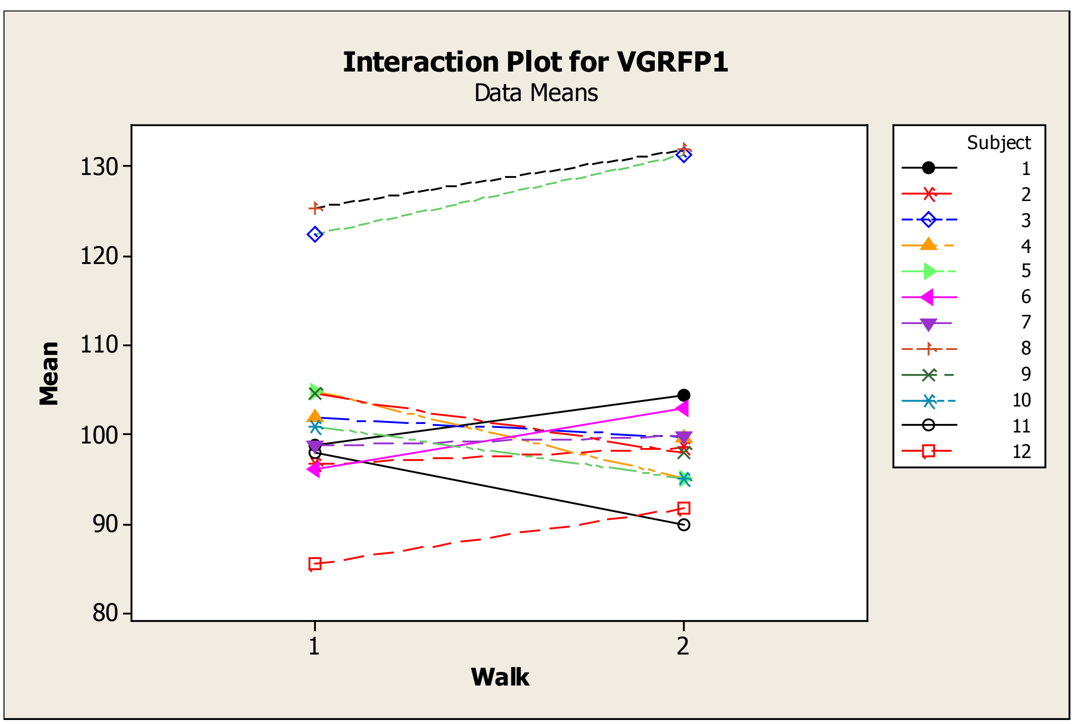


Figure 4.16 Interaction Plot for vertical GRF (F_z) Peak1.

VGRFP2

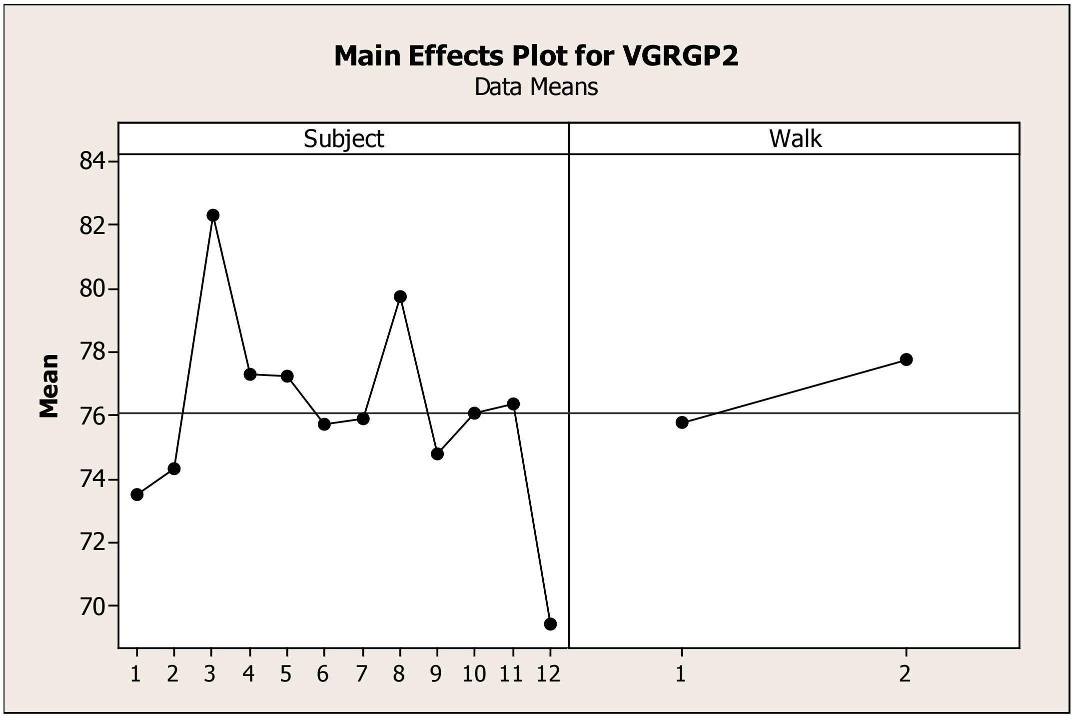


Figure 4.17 Main Effects Plot for vertical GRF (F_z) Peak2.

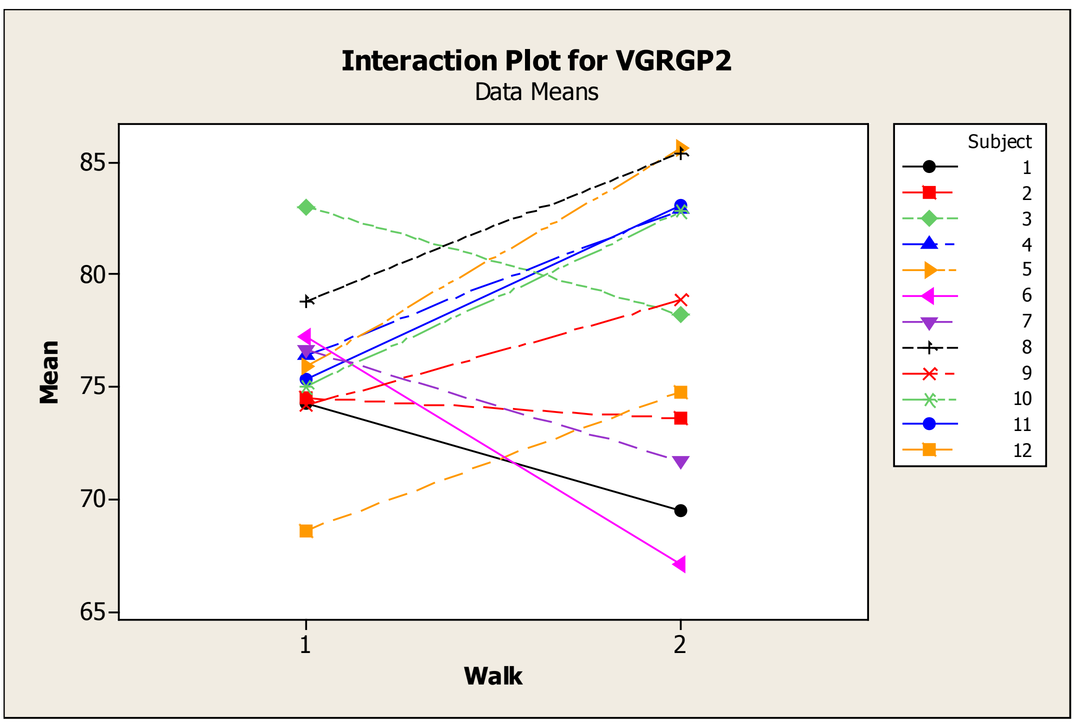


Figure 4.18 Interaction Plot for vertical GRF (F_z) Peak2.

VGRFP3

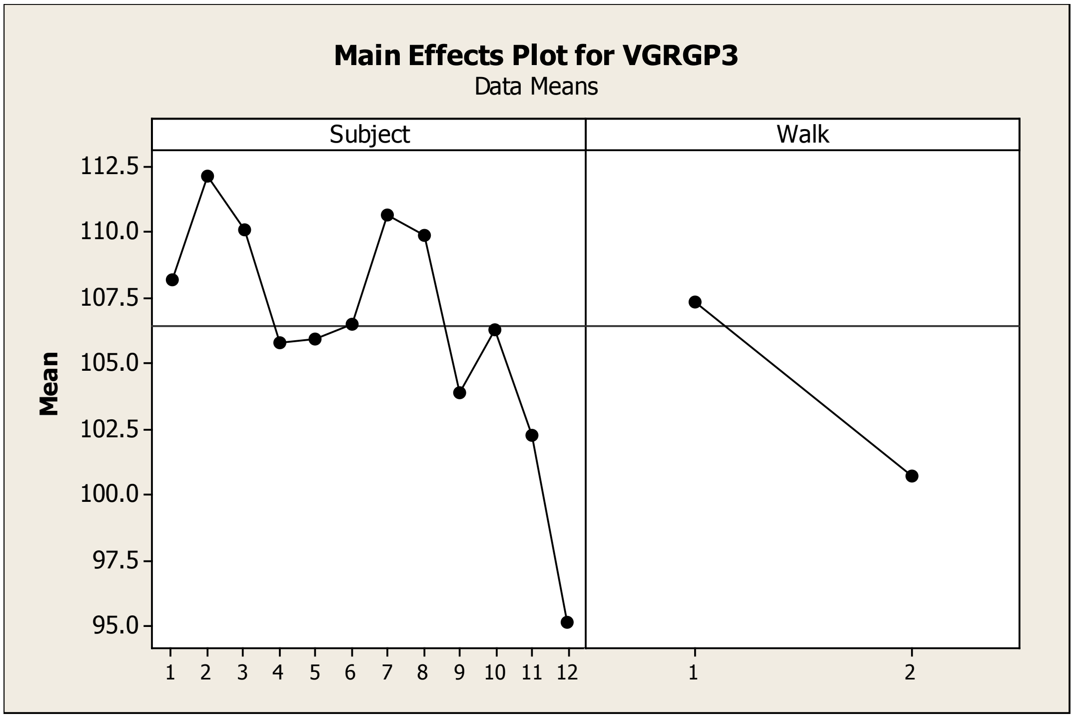


Figure 4.19 Main Effects Plot for vertical GRF (F_z) Peak3.

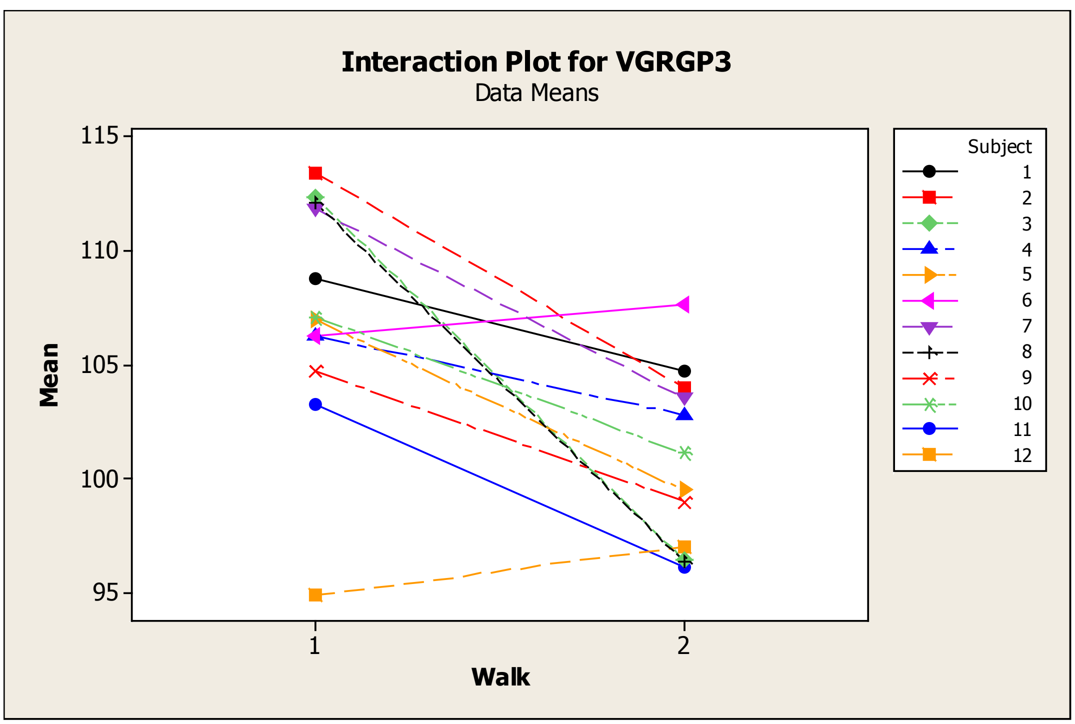


Figure 4.20 Interaction Plot for vertical GRF (F_z) Peak3.

APGRFP1

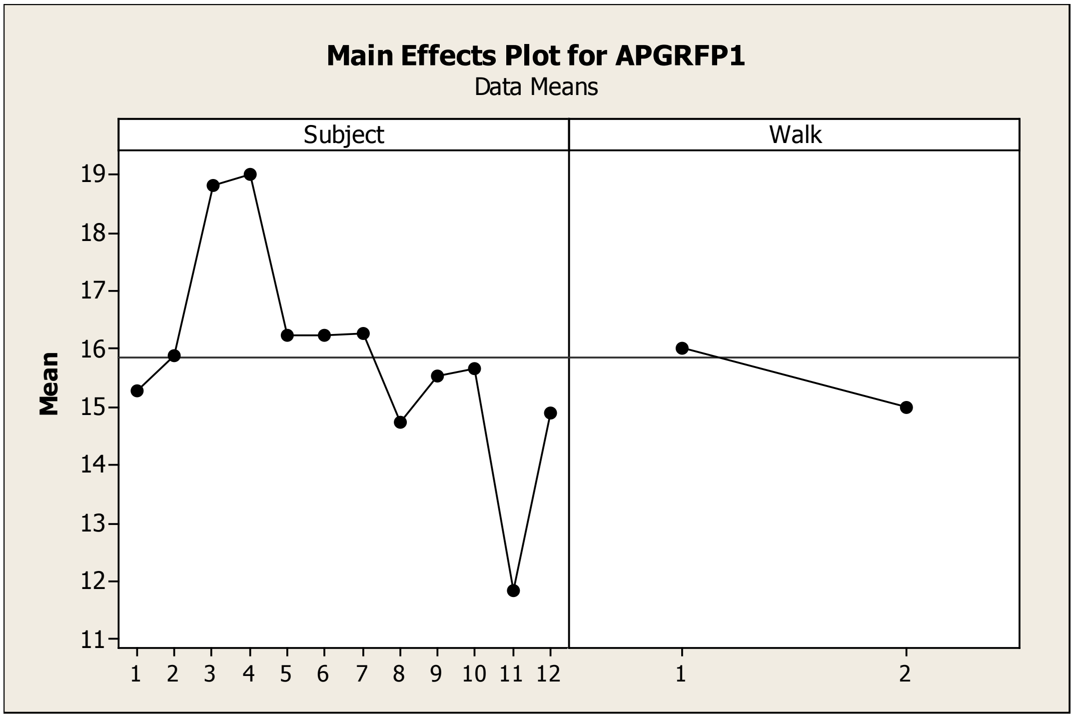


Figure 4.21 Main Effects Plot for anterior/posterior GRF (F_{AP}) Peak1.

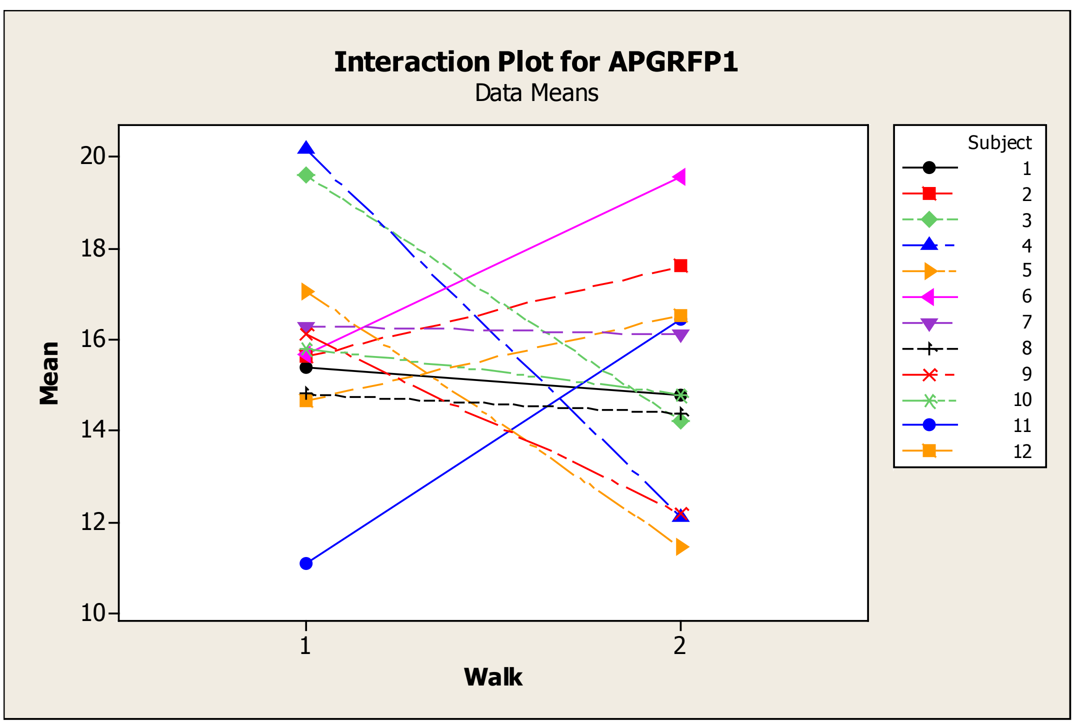


Figure 4.22 Interaction plot for anterior/posterior GRF (F_{AP}) Peak1.

APGRFP2

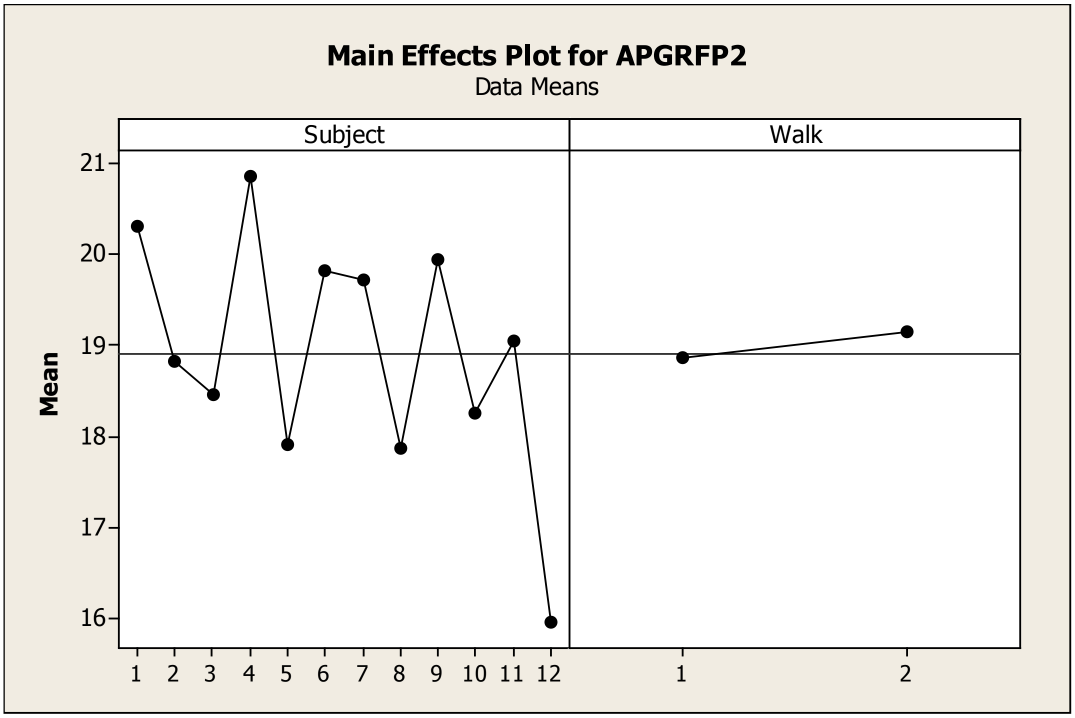


Figure 4.23 Main Effects Plot for anterior/posterior GRF (F_{AP}) Peak2.

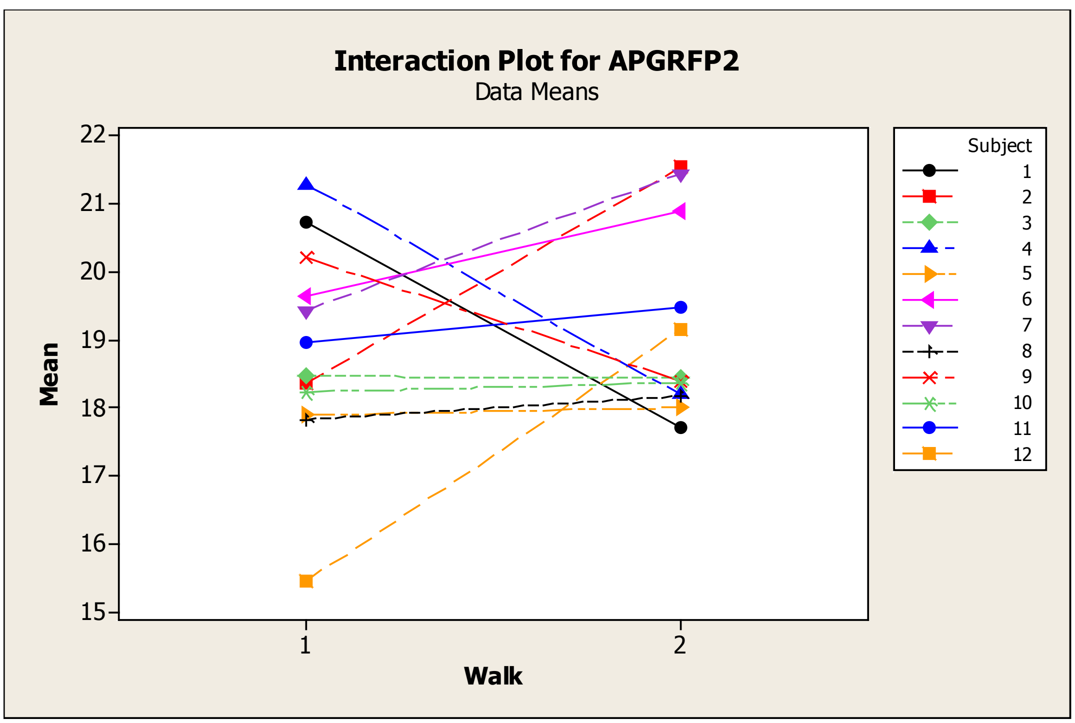


Figure 4.24 Interaction plot for anterior/posterior GRF (F_{AP}) Peak2.

MLGRFP1

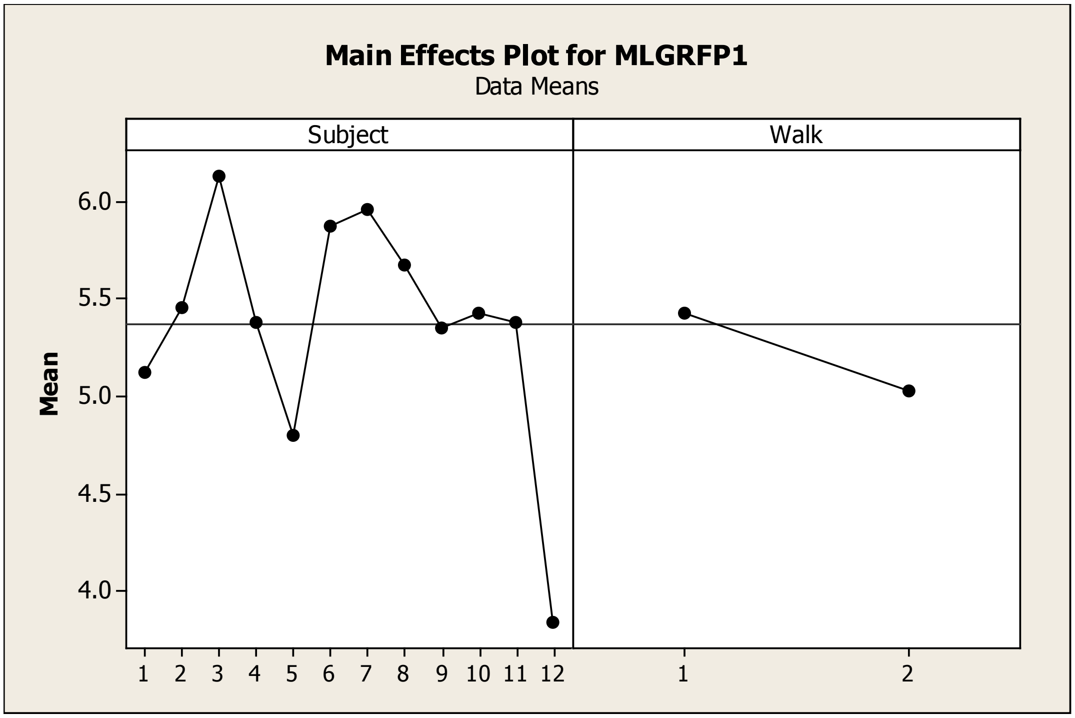


Figure 4.25 Main Effects Plot for medial/lateral GRF (F_{ML}) Peak1.

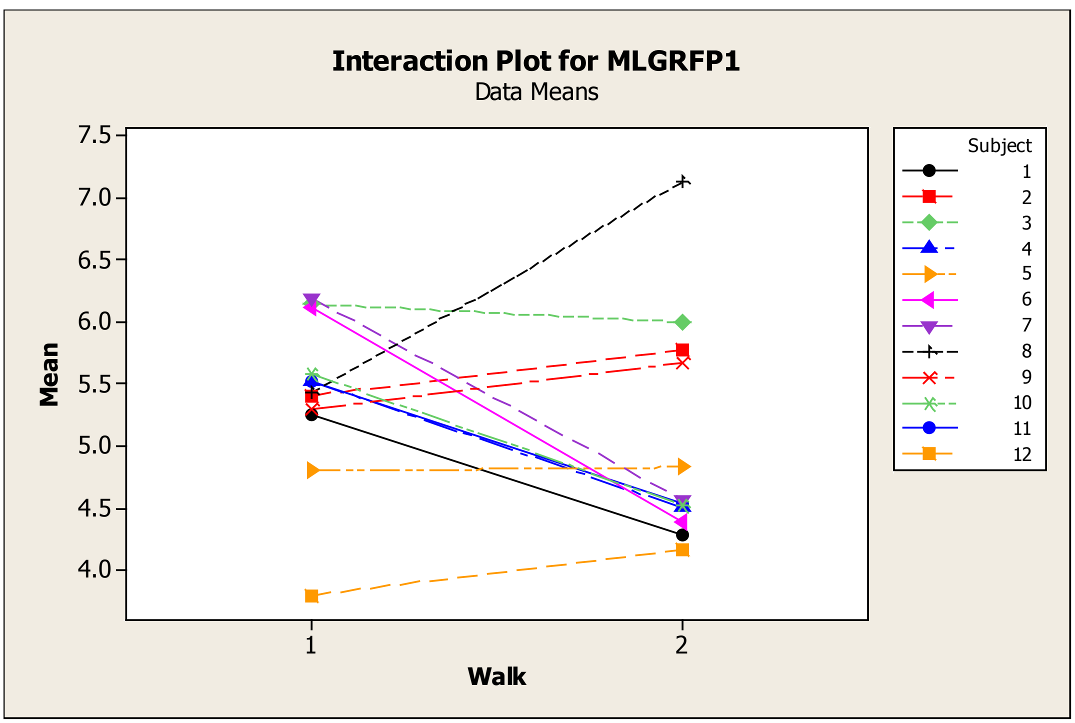


Figure 4.26 Interaction Plot for medial/lateral GRF (F_{ML}) Peak1.

MLGRFP2

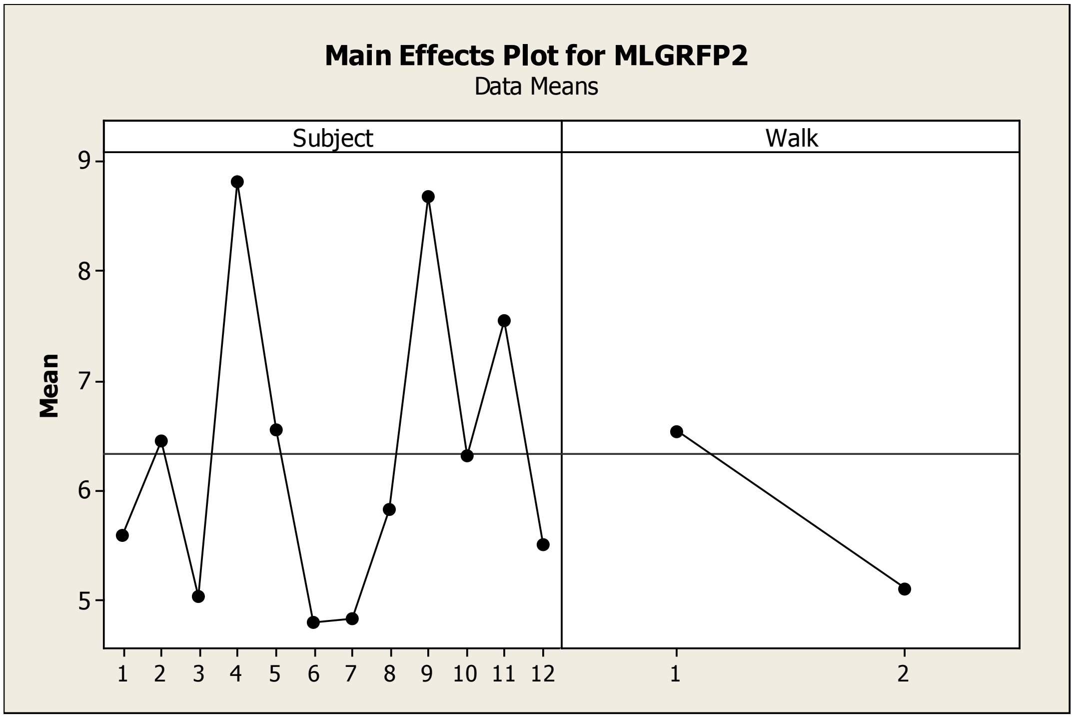


Figure 4.27 Main Effects Plot for medial/lateral GRF (F_{ML}) Peak2.

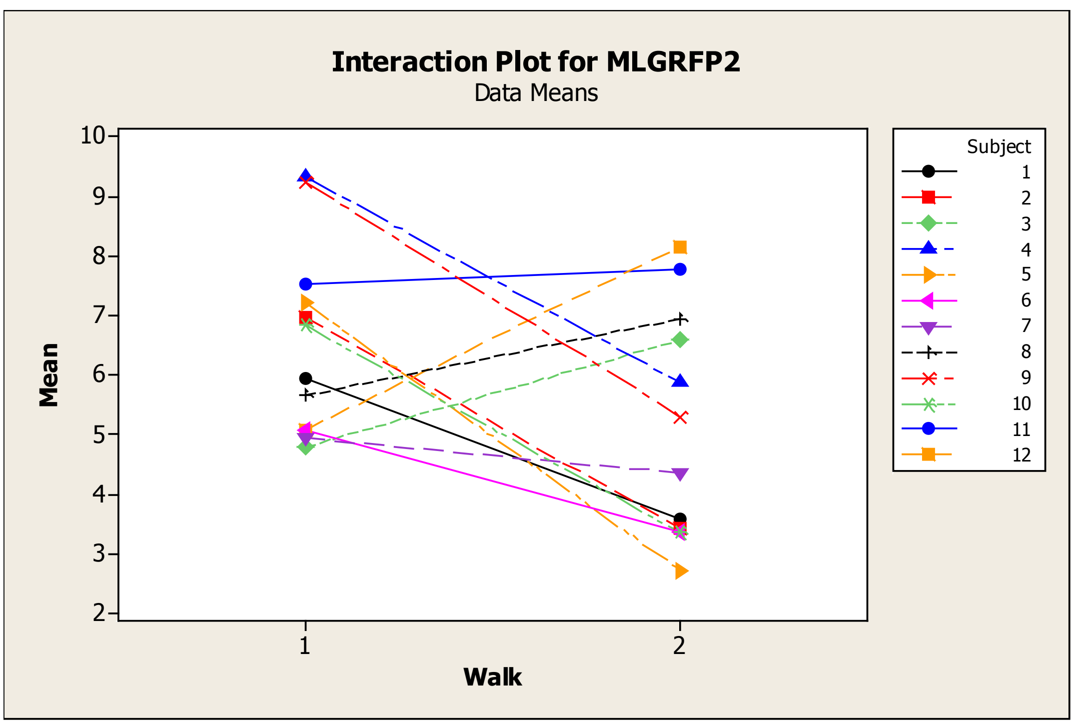


Figure 4.28 Interaction plot for medial/lateral GRF (F_{ML}) Peak2.

In examining the Main Effects Plots (Figures 4.15, 4.17, 4.19, 4.21, 4.23, 4.25 and 4.27), the Interactions Plots (Figures 4.16, 4.18, 4.20, 4.22, 4.24, 4.26 and 4.28), and the Scatterplots of response variable versus subject (Figures 4.8 through 4.14), it is seen without clear consistency that overground walking (Walk 1) has higher response variables values for some subjects, and treadmill walking (Walk 2) has higher response variables values for others. Hence, the presence of an interaction doesn't influence the results in the Walk Type column of Table 4.3 (i.e., the results obtained from GLM for repeated measures). The values of the Walk Type column of Table 4.3 indicate that for VGRFP1, VGRFP2, APGRFP1, APGRFP2 and MLGRFP1, there is no overall statistically detectable differences between the two walking styles at p=0.05. However, that much variability exists among the subjects must be noted.

A regression approach was used in an attempt to estimate associations between components of GRF in treadmill walking and various measurements which can be obtained during an overground walking trial. Possible predictor variables include the subjects' height (*H*), weight (*W*), walking speed (*S*), the point of the gait cycle at which terminal contact (Foot off) occur (*FO*), stride time (*SrTime*), step time (*SpTime*), stride length (*SrLength*), step length (*SpLength*) in addition to the overground measurement for the corresponding treadmill measurement we are attempting to predict. The number of predictors to be included in the multiple regression models was limited to two predictors in each model due to the small number of subjects in this study. We attempted to include the average of the six overground trials for each response variable in every model for the corresponding response variable associated with the Treadmill. However, in some cases, due to the lack of a linear relationship between the treadmill walk and the average of the overground walks, the inclusion of such variable as a predictor in the regression model did not yield significant results and therefore it was excluded.

All treadmill GRF components were studied via the regression approach however only regression equations for the following treadmill GRF components were found to be significant to estimate the desired association. The following regression equations are for the three peaks of Vertical Ground reaction force (VGRFP1, VGRFP2, and VGRFP3), the first peaks of Anterior/Posterior Ground Reaction Force (APGRFP1) and the first peak of the Medial/Lateral (MLGRFP1). The developed equations are as follow:

1. **VGRFP1_TM = -11.2 + 1.11VGRFP1_OG** (adjusted-R^2 = 75.9%)
2. **VGRFP2_TM = -49.2 + 2.23*FO*** (adjusted-R^2 = 37.5%)
3. **VGRFP3_TM = 142 + 0.363VGRFP3_OG – 140*SpTime*** (adjusted-R^2 = 59.9%)
4. **APGRFP1_TM = 113 - 1.25*FO* – 47.7*SpLength*** (adjusted-R^2 = 29.6%)
5. **MLGRFP1_TM = -11.6 + 0.292*FO*** (adjusted-R^2 = 40.1%)

Chapter 5
Discussion, Conclusion, and Recommendations

5.1 Discussion:

The Shapiro-Wilks W test is the standard test for normality and is recommended for smaller samples. The test suggests that some data in our study do not follow a normal distribution. Specifically that test indicates that at the p=0.05 level data in the first peak of the vertical ground reaction force during overground walking (AvgOG_VGRFP1), the first peak of the vertical ground reaction force during treadmill walking (TM_VGRFP1), the second peak of the anterior-posterior ground reaction force during treadmill walking (TM_APGRFP2), and the first peak of the medial-lateral ground reaction force during treadmill walking (TM_MLGRFP1) are not normally distributed. Additionally the Shapiro-Wilks W test points to that at p=0.10 level data in the third peak of the vertical ground reaction force during overground walking (AvgOG_VGRFP3), and in the second peak of the medial-lateral ground reaction force during overground walking (AvgOG_MLGRFP2) are not normally distributed.

The Wilcoxon Signed Rank test was performed with the mean of the six overground walk measurements compared to the treadmill walk measurement, for each of the seven different measurement types and for each of the twelve subjects. The Wilcoxon test calculates if the average of the overground walks is significantly different from the treadmill walk. At the p=0.05 level, the Wilcoxon Signed Rank test suggests that the third peak of vertical ground reaction force (VGRFP3) is significantly different in treadmill walking from the average overground walking. Also, at the p=0.10 level, the second peak of medial-lateral ground reaction force (MLGRFP2) is significantly different in the treadmill walking from the overground walking. The test did not detect any significant differences between treadmill walking and overground walking in the first and second peaks of vertical ground reaction force (VGRFP1 and VGRFP2), in the first and second peaks of anterior-posterior ground reaction force (APGRFP1 and APGRFP2), or in the first peak of medial-lateral ground reaction force (MLGRFP1). The Wilcoxon Signed Rank test uses the average of the overground walks so it does not directly take into account the repeated measurement of the overground walks. Also, this test does not directly take into account the between-subjects effects (the inter-subject variability).

Unlike the Wilcoxon Signed Rank test, the GLM Repeated Measures model takes into account all six of the overground measurements for each subject and not the average of these overground trials. Additionally this model accounts for the study subjects by assessing inter-subject variability. The residual normal probability plots obtained for each response variable (Appendix D) do not provide any reason to suspect departure from normality for thr residuals of the GLM Repeated Measures Model. The results of the GLM Repeated Measures Model indicate that the overground walking observations were significantly different from the treadmill walking observations for some of the measurement types, but not others. Specifically, at p=0.05, the third peak of the vertical ground reaction force and the second peak of the medial-lateral ground reaction force were significantly different in overground gait from treadmill gait. The model also indicated that the Subject/Walk Type interaction was significantly different at the p=0.05 level for all response variables but one: first peak of medial-lateral ground reaction force (MLGRFP1). Main Effects Plots and Interaction Plots for each peak in the components of GRF as well as Scatterplots of Response variable versus Subject were used to study if the existence of this interaction swayed the results. Although high variability among the subjects exists, and Subject / Walk Type interaction is statistically significant the plots suggest that the presence of such interaction does not influence the results in the Walk Type. In other words, the inter subject variability did not influence whether the overground gait is significantly different from treadmill gait or not. Since the small sample size might severely restrict the power of analysis to detect differences even if they exist then we should note that the results of the GLM for repeated measures test are suggestive of existence of statistical differences that did not meet the threshold of p=0.05 statistical significance between overground gait and treadmill gait in the second peak of the vertical ground reaction force (VGRFP2) and the first peak of the anterior-posterior ground reaction force (APGRFP1).

The GLM for repeated measures test detects the same significant differences uncovered by the Wilcoxon Signed Rank test. This finding gives us more confident to confirm that the third peak of vertical ground reaction force (VGRFP3) and the second peak of medial-lateral ground reaction force (MLGRFP1) are statistically different during overground locomotion from treadmill locomotion.

Most experiments have certain statistical limitations when it comes to analyzing the data and interpreting the results. It is imperative to mention that, in our experiment, to set the walking speed during treadmill walking for each subject we averaged the subject's speed from the six overground walking trials. This may create some dependence between the two data. Using usual statistical procedures we cannot establish equivalence; therefore, when the analysis does not indicate a difference between response variables, this would only imply that we were not able to detect one. The reason could be because in reality there is no differences between the response variables or because the experiment was not powered enough to detect it.

5.2 Conclusion & Recommendations:

The aim of this research was to examine a method by which components of GRFs are measured by placing a treadmill on top of four floor mounted force platforms. The use of treadmills has always been popular in physical rehabilitation centers, and it is becoming increasingly more common in gait laboratories. Such laboratories are typically equipped with floor embedded force platform(s) allowing the analysis of only one or two consecutive steps. Treadmills allow for the collection of multiple consecutive steps in a small space, and the ability to study walking patterns over a prolonged period of time. Collecting forces exerted during locomotion allows for kinetic analyses during treadmill ambulation. However, acquiring instrumented treadmills–treadmill with a built in force plate(s)–may not be financially feasible for many general purpose biomechanics laboratories; additionally many instrumented treadmills only measure the vertical component of GRF. The examined method seeks to be a solution in such situations.

The pattern and amplitude of force-time curves for all components of ground reaction force (Figure 5.1) obtained during treadmill walking were similar to data obtained during overground walking; indicating that acceleration patterns are similar during the stance phase of the gait cycle (Nilsson and Thorstensson 1989; White, Yack et al. 1998). Increased absolute forces during loading response for VGRF (P1), MLGRF (P1), and APGRF (P1) and through push off for VGRF (P3), MLGRF (P2), and APGRF (P2) , as well as minimal forces below body weight during mid-stance for VGRF (P2) are characteristics evident in treadmill walking and overground walking.

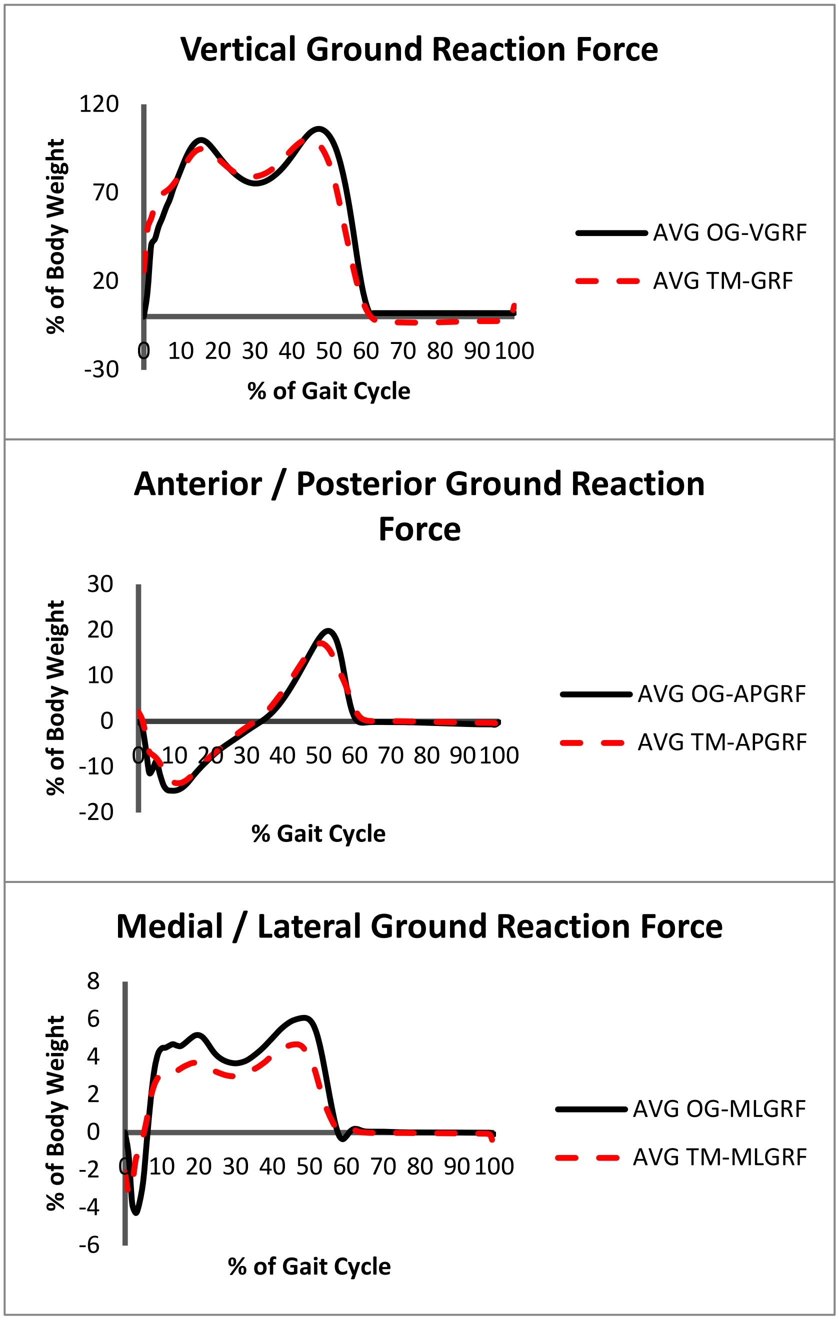


Figure 5.1 Patterns of Ground Reaction Force in Overground and Treadmill Walking

The analysis of the data did not reveal statistical differences in the anterior-posterior component of the GRF (APGRFP1 and APGRFP2) and in the early-stance and mid-stance peaks of the vertical GRF (VGRFP1 and VGRFP2) ($p < 0.05$) between treadmill and overground walking. The findings are in agreement with the reporting of Kram et al. and Riley et al (Kram, Griffin et al. 1998; Riley, Paolini et al. 2007). Both studies found that anterior-posterior and vertical components of the GRF in treadmill and overground locomotion to be very similar.

Statistical differences between treadmill and overground walking were found during late-stance for vertical ground reaction force (VGRFP3) and medial lateral ground reaction force (MLGRFP2) ($p < 0.05$). During push-off- occurring in late-stance-vertical ground reaction force peaks (VGRFP3) were less in treadmill walking than in overground walking by 5 – 6%. The medial-lateral ground reaction forces peaks (MLGRFP2) were also less in treadmill walking than in overground walking by 1 – 2%. The force peaks during push-off are related to the extension of support limb during late-stance. Not extending limb fully would result in a shorter stride length. Several authors have reported decreased stride length as one of the differences between treadmill and overground walking. Stolz et al. noted that step frequency increased by 7% in adults and by 10% in children while stride length and stance phase decreased during treadmill walking in comparison to overground walking (Stolze, Kuhtz-Buschbeck et al. 1997). Alton et al. reported that stance phase was shortened significantly in treadmill walking when human locomotion was analyzed on the treadmill and on the ground for identical walking speed (Alton, Baldey et al. 1998). Others also reported similar variability of steps and several kinematic measurements Murray et al. (Murray, Spurr et al. 1985), Dingwell et al. (Dingwell, Cusumano et al. 2001) and Owings and Grabiner (Owings and Grabiner 2004).

Another explanation for the reduced peaks of ground reaction force in late stance would be the effect of treadmill belt speed fluctuations on the subject. Braking (shear) forces are at maximum during limb loading in early stance and frictional forces increase, as a result the belt speed slows down causing the subject to exert negative work on the treadmill. White et al. warned that “the potential for lower push-off forces should be considered when interpreting treadmill locomotion particularly for higher speeds and for heavier individuals since belt friction forces will increase with body mass” (White, Yack et al. 1998). van Ingen Schenau pointed out that treadmill speed had to be constant for dynamic similarity between treadmill and overground gait (van Ingen Schenau 1980). Savelberg et al. also observed a 5% decrease in belt speed in the braking phase in high-power treadmill (Savelberg, Vorstenbosch et al. 1998).

Five regression equations were developed to estimate associations between components of GRF in treadmill walking and various measurements which can be obtained during an overground walking trial. The equations can be used for Vertical Ground Reaction Force Peak 1 (VGRFP1), Vertical Ground Reaction Force Peak 2 (VGRFP2), Vertical Ground Reaction Force Peak 3 (VGRFP3), Anterior – Posterior Ground Reaction Force Peak 1 (APGRFP1), and Medial – Lateral Ground Reaction Force Peak 1 (MLGRFP1) for treadmill walking.

We must realize that treadmill walking has some drawbacks; for example, some patients are more anxious when walking on a treadmill. Patients must be trained on treadmill walking prior to collecting data. Additionally, our method collects the summed ground reaction forces from both feet which is not suitable for joint moments assessment. However, an algorithm to separate the individual vertical forces for each foot can be used before computing joint moments (Davis and Cavanagh 1993). Despite the drawbacks, treadmill walking has many advantages for example Dierick, Penta et al. highlighted some of the advantages of using treadmills over ground walking by stating "It allows a decrease in the data collection time and the space required, and to record GRFs at constant gait speeds. Moreover, it also allows recording the GRFs, the kinematics, EMG, and rate of oxygen consumption simultaneously" Therefore, we should judge the utility of using a treadmill on the balance of its advantages and disadvantages (Dierick, Penta et al. 2004)

Additional work is needed to confirm the results, and to collect data and validate the methodology across pathologies. Suggestions for future work include using male and female subjects, using subjects with known pathologies to test the current methodology's ability to detect such pathologies, and using markers on subjects during both overground and treadmill trials to further utilize the Vicon's system ability to calculate kinetics and kinematics data.

Appendix A
Subjects' Questionnaire

Name:________________________________
Age:_____________ Height:____________ Weight:___________

Are you Right or Left handed? ____________________

Have you ever had any Foot injury? ___________________________

If yes, Explain:____

Have you ever had any Ankle injury? ___________________________

If yes, Explain: ____

Have you ever had any Leg injury? ___________________________

If yes, Explain: ____

Have you ever had any Knee injury? ___________________________

If yes, Explain: ____

Have you ever had any Thigh injury? ___________________________

If yes, Explain: ____

Have you ever had any Hip/Pelvis injury? ___________________________

If yes, Explain: ____

Have you ever had any Other Musculoskeletal injury? ___________________________

If yes, Explain: ____

Have you ever used a Treadmill before? ______________________________

If yes, please rate your use of the treadmill from 0 to 7: ______________________

(0: less than once a week, 1: once a week, 2: twice a week ……..7: 7 times a week)

Are you willing to come to the Biomechanics Research Lab for an hour to an hour and half on two separate times on a MONDAY? _________________

If yes, What time? ____

Are you willing to come to the Biomechanics Research Lab for an hour to an hour and half on two separate times on a FRIDAY? _________________

If yes, What time? ____

Are you willing to come to the Biomechanics Research Lab for an hour to an hour and half on two separate times on a SATURDAY? _________________

If yes, What time? ____

Are you willing to come to the Biomechanics Research Lab for an hour to an hour and half on two separate times on a SUNDAY? _________________

If yes, What time? ____

<u>CONTACT INFORMATION:</u>

Email: ____

Phone Number: ______________________________________

Appendix B
SAS Results for Shapiro-Wilk Test for Normality

The SAS System
The UNIVARIATE Procedure
Variable: AvgOG_VGRFP1
Tests for Normality

Test	--Statistic---		-----p Value------	
Shapiro-Wilk	W	0.854976	Pr < W	0.0423
Kolmogorov-Smirnov	D	0.261976	Pr > D	0.0223
Cramer-von Mises	W-Sq	0.162441	Pr > W-Sq	0.0144
Anderson-Darling	A-Sq	0.88813	Pr > A-Sq	0.0172

The SAS System
The UNIVARIATE Procedure
Variable: TM_VGRFP1
Tests for Normality

Test	--Statistic---		-----p Value------	
Shapiro-Wilk	W	**0.744296**	Pr < W	**0.0023**
Kolmogorov-Smirnov	D	**0.296673**	Pr > D	<**0.0100**
Cramer-von Mises	W-Sq	**0.235602**	Pr > W-Sq	<**0.0050**
Anderson-Darling	A-Sq	**1.349206**	Pr > A-Sq	<**0.0050**

The SAS System
The UNIVARIATE Procedure
Variable: AvgOG_VGRFP2
Tests for Normality

Test	--Statistic---		-----p Value------	
Shapiro-Wilk	W	0.912352	Pr < W	0.2287
Kolmogorov-Smirnov	D	0.226768	Pr > D	0.0869
Cramer-von Mises	W-Sq	0.096325	Pr > W-Sq	0.1141
Anderson-Darling	A-Sq	0.574041	Pr > A-Sq	0.1087

The SAS System
The UNIVARIATE Procedure
Variable: TM_VGRFP2
Tests for Normality

Test	--Statistic---		-----p Value------	
Shapiro-Wilk	W	**0.925745**	Pr < W	**0.3372**
Kolmogorov-Smirnov	D	**0.200829**	Pr > D	>**0.1500**
Cramer-von Mises	W-Sq	**0.055653**	Pr > W-Sq	>**0.2500**
Anderson-Darling	A-Sq	**0.35633**	Pr > A-Sq	>**0.2500**

The SAS System
The UNIVARIATE Procedure
Variable: AvgOG_VGRFP3
Tests for Normality

Test	--Statistic---		-----p Value------	
Shapiro-Wilk	W	0.932432	Pr < W	0.4066
Kolmogorov-Smirnov	D	0.161618	Pr > D	>0.1500
Cramer-von Mises	W-Sq	0.048996	Pr > W-Sq	>0.2500
Anderson-Darling	A-Sq	0.348649	Pr > A-Sq	>0.2500

The SAS System
The UNIVARIATE Procedure
Variable: TM_VGRFP3
Tests for Normality

Test	--Statistic---		-----p Value------	
Shapiro-Wilk	W	**0.922474**	Pr < W	**0.3071**
Kolmogorov-Smirnov	D	**0.162507**	Pr > D	>**0.1500**
Cramer-von Mises	W-Sq	**0.053047**	Pr > W-Sq	>**0.2500**
Anderson-Darling	A-Sq	**0.366474**	Pr > A-Sq	>**0.2500**

The SAS System
The UNIVARIATE Procedure
Variable: AvgOG_APGRFP1
Tests for Normality

Test	--Statistic---		-----p Value------	
Shapiro-Wilk	W	0.90399	Pr < W	0.1786
Kolmogorov-Smirnov	D	0.203246	Pr > D	>0.1500
Cramer-von Mises	W-Sq	0.115236	Pr > W-Sq	0.0636
Anderson-Darling	A-Sq	0.636625	Pr > A-Sq	0.0771

The SAS System
The UNIVARIATE Procedure
Variable: TM_APGRFP1
Tests for Normality

Test	--Statistic---		-----p Value------	
Shapiro-Wilk	W	**0.9622**	Pr < W	**0.8147**
Kolmogorov-Smirnov	D	**0.131718**	Pr > D	>**0.1500**
Cramer-von Mises	W-Sq	**0.034726**	Pr > W-Sq	>**0.2500**
Anderson-Darling	A-Sq	**0.235979**	Pr > A-Sq	>**0.2500**

The SAS System
The UNIVARIATE Procedure
Variable: AvgOG_APGRFP2
Tests for Normality

Test	--Statistic---		-----p Value------	
Shapiro-Wilk	W	0.954191	Pr < W	0.6988
Kolmogorov-Smirnov	D	0.16295	Pr > D	>0.1500
Cramer-von Mises	W-Sq	0.036076	Pr > W-Sq	>0.2500
Anderson-Darling	A-Sq	0.26427	Pr > A-Sq	>0.2500

The SAS System
The UNIVARIATE Procedure
Variable: TM_APGRFP2
Tests for Normality

Test	--Statistic---		-----p Value------	
Shapiro-Wilk	W	**0.821642**	Pr < W	**0.0167**
Kolmogorov-Smirnov	D	**0.277779**	Pr > D	**0.0114**
Cramer-von Mises	W-Sq	**0.163489**	Pr > W-Sq	**0.0138**
Anderson-Darling	A-Sq	**0.943173**	Pr > A-Sq	**0.0117**

The SAS System
The UNIVARIATE Procedure
Variable: AvgOG_MLGRFP1
Tests for Normality

Test	--Statistic---		-----p Value------	
Shapiro-Wilk	W	0.86442	Pr < W	0.0556
Kolmogorov-Smirnov	D	0.235161	Pr > D	0.0665
Cramer-von Mises	W-Sq	0.107718	Pr > W-Sq	0.0813
Anderson-Darling	A-Sq	0.652013	Pr > A-Sq	0.0703

The SAS System
The UNIVARIATE Procedure
Variable: TM_MLGRFP1
Tests for Normality

Test	--Statistic---		-----p Value------	
Shapiro-Wilk	W	**0.823926**	Pr < W	**0.0178**
Kolmogorov-Smirnov	D	**0.278273**	Pr > D	**0.0110**
Cramer-von Mises	W-Sq	**0.171597**	Pr > W-Sq	**0.0098**
Anderson-Darling	A-Sq	**0.929459**	Pr > A-Sq	**0.0130**

The SAS System
The UNIVARIATE Procedure
Variable: AvgOG_MLGRFP2
Tests for Normality

Test	--Statistic---		-----p Value------	
Shapiro-Wilk	W	0.889981	Pr < W	0.1178
Kolmogorov-Smirnov	D	0.155437	Pr > D	>0.1500
Cramer-von Mises	W-Sq	0.063166	Pr > W-Sq	>0.2500
Anderson-Darling	A-Sq	0.478453	Pr > A-Sq	0.1996

The SAS System
The UNIVARIATE Procedure
Variable: TM_MLGRFP2
Tests for Normality

Test	--Statistic---		-----p Value------	
Shapiro-Wilk	W	**0.905789**	Pr < W	**0.1884**
Kolmogorov-Smirnov	D	**0.206966**	Pr > D	>**0.1500**
Cramer-von Mises	W-Sq	**0.074772**	Pr > W-Sq	**0.2271**
Anderson-Darling	A-Sq	**0.471373**	Pr > A-Sq	**0.2080**

Appendix C
SAS Results for The Wilcoxon Signed Rank Test for Simple Association

```
                    The SAS System
 Paired t-test and nonparametric tests using proc univariate

               The UNIVARIATE Procedure
                Variable:  diffVGRFP1
              Tests for Location: Mu0=0
 Test             -Statistic-    -----p Value------

 Student's t     t  0.198138    Pr > |t|    0.8466
 Sign            M         1    Pr >= |M|   0.7744
 Signed Rank     S         1    Pr >= |S|   0.9697
```

```
                    The SAS System
 Paired t-test and nonparametric tests using proc univariate

               The UNIVARIATE Procedure
                Variable:  diffVGRFP2
              Tests for Location: Mu0=0
 Test             -Statistic-    -----p Value------

 Student's t     t  1.021585    Pr > |t|    0.3289
 Sign            M         1    Pr >= |M|   0.7744
 Signed Rank     S        14    Pr >= |S|   0.3013
```

```
                    The SAS System
 Paired t-test and nonparametric tests using proc univariate

               The UNIVARIATE Procedure
                Variable:  diffVGRFP3
              Tests for Location: Mu0=0
 Test             -Statistic-    -----p Value------

 Student's t     t  -4.60186    Pr > |t|    0.0008
 Sign            M        -5    Pr >= |M|   0.0063
 Signed Rank     S       -37    Pr >= |S|   0.0015
```

```
                    The SAS System
Paired t-test and nonparametric tests using proc univariate

               The UNIVARIATE Procedure
                Variable:  diffAPGRFP1
              Tests for Location: Mu0=0
     Test           -Statistic-    -----p Value------
     Student's t    t   -0.8577    Pr > |t|    0.4094
     Sign           M        -2    Pr >= |M|   0.3877
     Signed Rank    S       -12    Pr >= |S|   0.3804
```

```
                    The SAS System
Paired t-test and nonparametric tests using proc univariate

               The UNIVARIATE Procedure
                Variable:  diffAPGRFP2
              Tests for Location: Mu0=0
     Test           -Statistic-    -----p Value------

     Student's t    t  0.404851    Pr > |t|    0.6933
     Sign           M         2    Pr >= |M|   0.3877
     Signed Rank    S        11    Pr >= |S|   0.4238
```

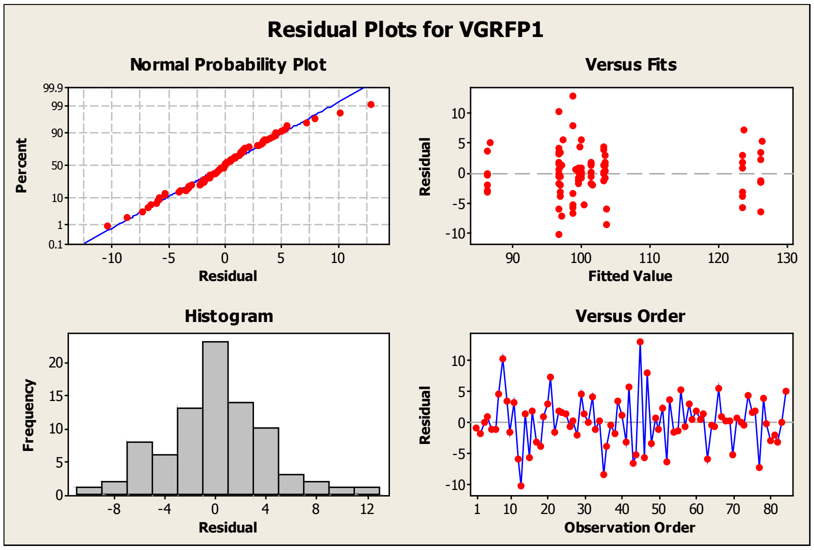
```
                    The SAS System
Paired t-test and nonparametric tests using proc univariate

               The UNIVARIATE Procedure
                Variable:  diffMLGRFP1
              Tests for Location: Mu0=0
     Test           -Statistic-    -----p Value------

     Student's t    t  -1.34076    Pr > |t|    0.2070
     Sign           M        -1    Pr >= |M|   0.7744
     Signed Rank    S       -15    Pr >= |S|   0.2661
```

```
                    The SAS System
Paired t-test and nonparametric tests using proc univariate

               The UNIVARIATE Procedure
                Variable:  diffMLGRFP2
              Tests for Location: Mu0=0
     Test           -Statistic-    -----p Value------

     Student's t    t  -1.94877    Pr > |t|    0.0773
     Sign           M        -2    Pr >= |M|   0.3877
     Signed Rank    S       -23    Pr >= |S|   0.0771
```

Appendix D
General Linear Model with Repeated Measures

MINITAB Results for General Linear Model: VGRFP1
General Linear Model: VGRFP1 versus Subject, Walk

```
Factor   Type    Levels  Values
Subject  random      12  1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Walk     fixed        2  1, 2


Analysis of Variance for VGRFP1, using Adjusted SS for Tests

Source   DF    Seq SS   Adj SS  Adj MS      F      P
Subject  11   9763.23  9763.23  887.57  47.46  0.000
Walk      1      1.47     1.47    1.47   0.08  0.780
Error    71   1327.83  1327.83   18.70
Total    83  11092.53


S = 4.32456   R-Sq = 88.03%   R-Sq(adj) = 86.01%


Unusual Observations for VGRFP1

Obs   VGRFP1      Fit  SE Fit  Residual  St Resid
  8  107.120   96.830   1.646    10.290      2.57 R
 13   86.480   96.830   1.646   -10.350     -2.59 R
 35   95.100  103.700   2.002    -8.600     -2.24 R
 45  111.760   98.817   1.646    12.943      3.24 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable VGRFP1
All Pairwise Comparisons among Levels of Walk
Walk = 1  subtracted from:

Walk   Lower  Center  Upper  -----+---------+---------+---------+-
2     -2.311  0.3779  3.067  (----------------*----------------)
                             -----+---------+---------+---------+-
                               -1.5       0.0       1.5       3.0


Tukey Simultaneous Tests
Response Variable VGRFP1
All Pairwise Comparisons among Levels of Walk
Walk = 1  subtracted from:

      Difference       SE of           Adjusted
Walk    of Means  Difference  T-Value   P-Value
2         0.3779       1.348   0.2803    0.7801
```



General Linear Model: VGRFP1 versus Subject, Walk

Factor	Type	Levels	Values
Subject	random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Walk	fixed	2	1, 2

Analysis of Variance for VGRFP1, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	9763.23	5531.17	502.83	13.39	0.000
Walk	1	1.47	1.47	1.47	0.04	0.847
Subject*Walk	11	413.17	413.17	37.56	2.46	0.013
Error	60	914.66	914.66	15.24		
Total	83	11092.53				

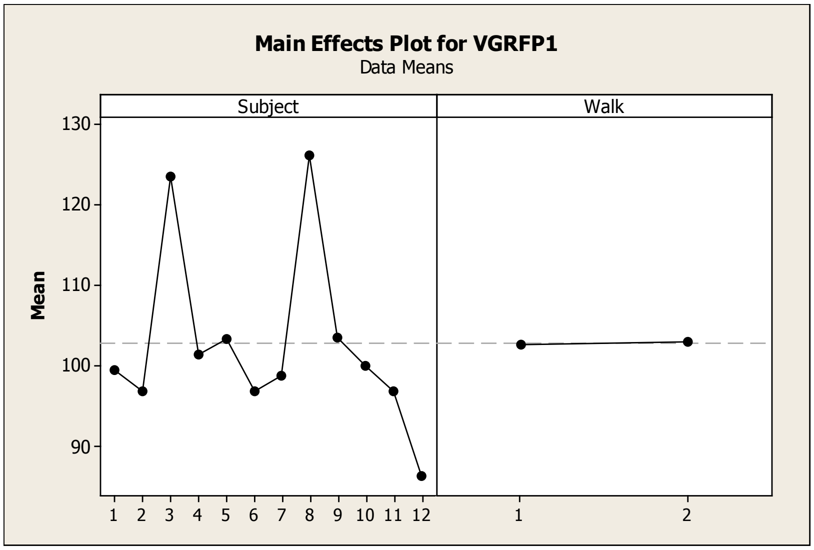
S = 3.90440   R-Sq = 91.75%   R-Sq(adj) = 88.59%

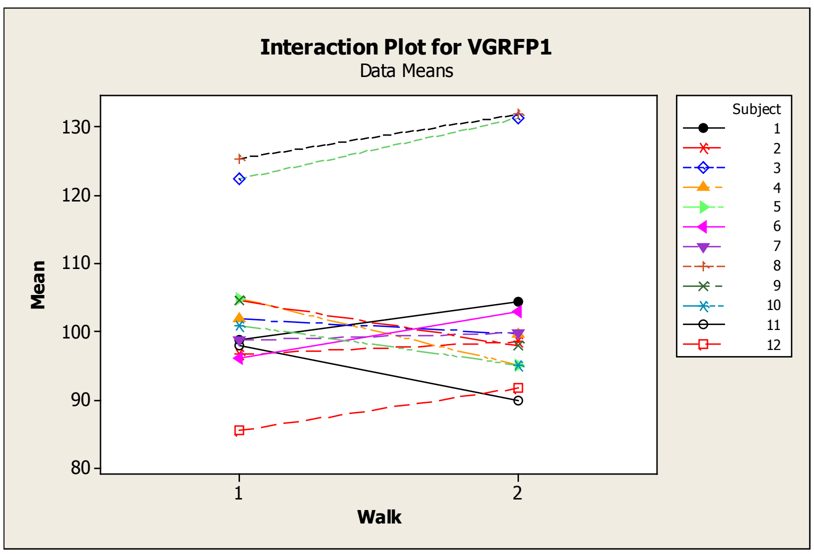
Unusual Observations for VGRFP1

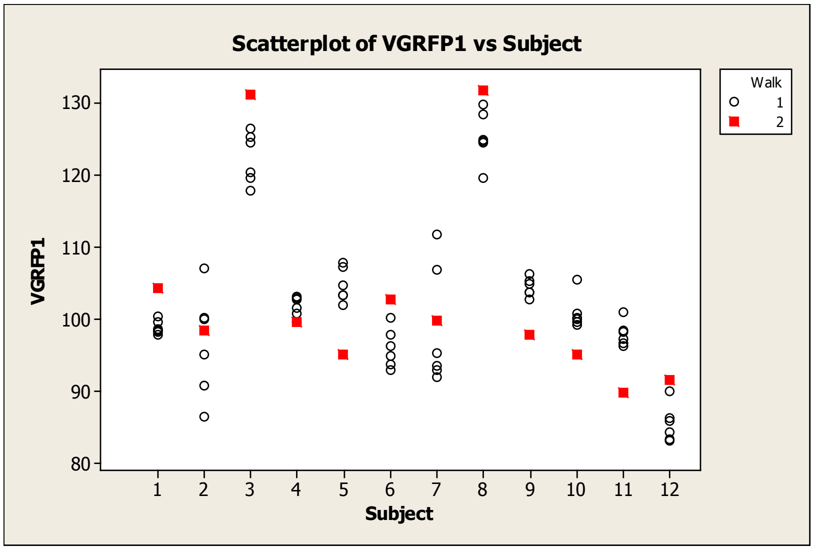
Obs	VGRFP1	Fit	SE Fit	Residual	St Resid	
7	104.430	104.430	3.904	0.000	*	X
8	107.120	96.622	1.594	10.498	2.95	R
13	86.480	96.622	1.594	-10.142	-2.85	R
14	98.460	98.460	3.904	-0.000	*	X
21	131.250	131.250	3.904	0.000	*	X
28	99.650	99.650	3.904	-0.000	*	X
35	95.100	95.100	3.904	0.000	*	X
42	102.850	102.850	3.904	-0.000	*	X
45	111.760	98.723	1.594	13.037	3.66	R
47	106.790	98.723	1.594	8.067	2.26	R
49	99.760	99.760	3.904	-0.000	*	X
56	131.820	131.820	3.904	0.000	*	X
63	97.900	97.900	3.904	0.000	*	X
70	95.030	95.030	3.904	0.000	*	X
77	89.860	89.860	3.904	-0.000	*	X
84	91.670	91.670	3.904	0.000	*	X

R denotes an observation with a large standardized residual.

```
X denotes an observation whose X value gives it large leverage.

* WARNING * No multiple comparisons were calculated for the following terms
            which contain or interact with random factors.
```





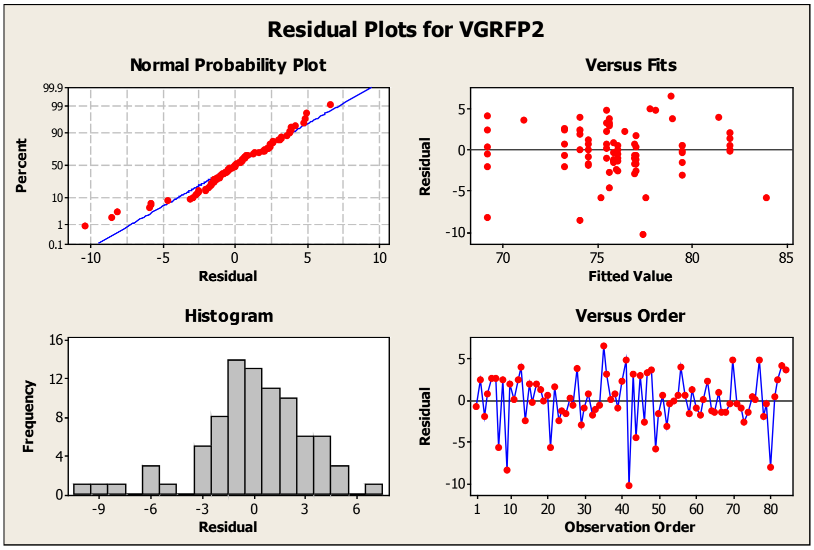


MINITAB Results for General Linear Model: VGRFP2

General Linear Model: VGRFP2 versus Subject, Walk

```
Factor    Type    Levels  Values
Subject   random      12  1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Walk      fixed        2  1, 2


Analysis of Variance for VGRFP2, using Adjusted SS for Tests

Source   DF   Seq SS  Adj SS  Adj MS     F      P
Subject  11   770.87  770.87   70.08  6.42  0.000
Walk      1    39.56   39.56   39.56  3.62  0.061
Error    71   775.32  775.32   10.92
Total    83  1585.75


S = 3.30454   R-Sq = 51.11%   R-Sq(adj) = 42.84%


Unusual Observations for VGRFP2

Obs   VGRFP2      Fit  SE Fit  Residual  St Resid
  9  65.5379  74.0833  1.2576   -8.5454     -2.80 R
 35  85.5580  78.9365  1.5297    6.6214      2.26 R
 42  67.0697  77.4325  1.5297  -10.3628     -3.54 R
 49  71.6915  77.6095  1.5297   -5.9181     -2.02 R
 80  60.9945  69.1837  1.2576   -8.1893     -2.68 R

R denotes an observation with a large standardized residual.


Grouping Information Using Tukey Method and 95.0% Confidence

Walk   N   Mean  Grouping
2     12  77.76  A
1     72  75.80  A

Means that do not share a letter are significantly different.
```

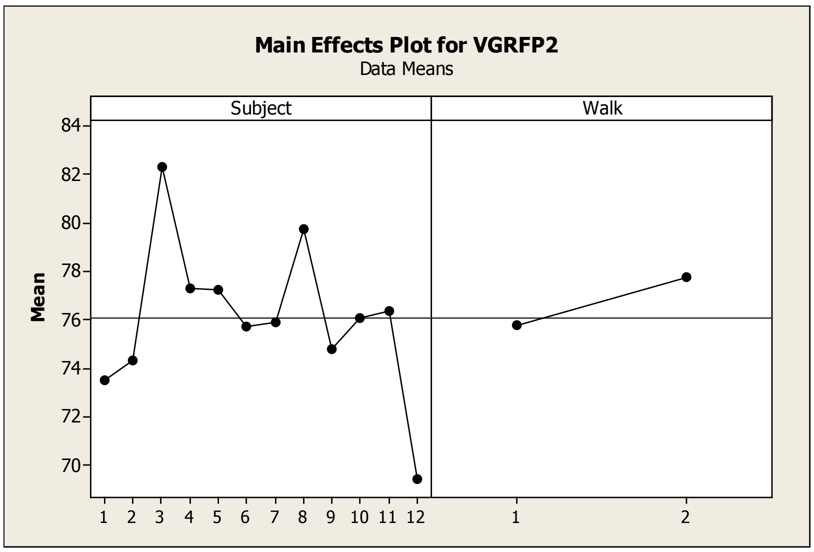
```
Tukey Simultaneous Tests
Response Variable VGRFP2
All Pairwise Comparisons among Levels of Walk
Walk = 1  subtracted from:

      Difference        SE of              Adjusted
Walk    of Means   Difference   T-Value     P-Value
2          1.961        1.030     1.903      0.0611
```

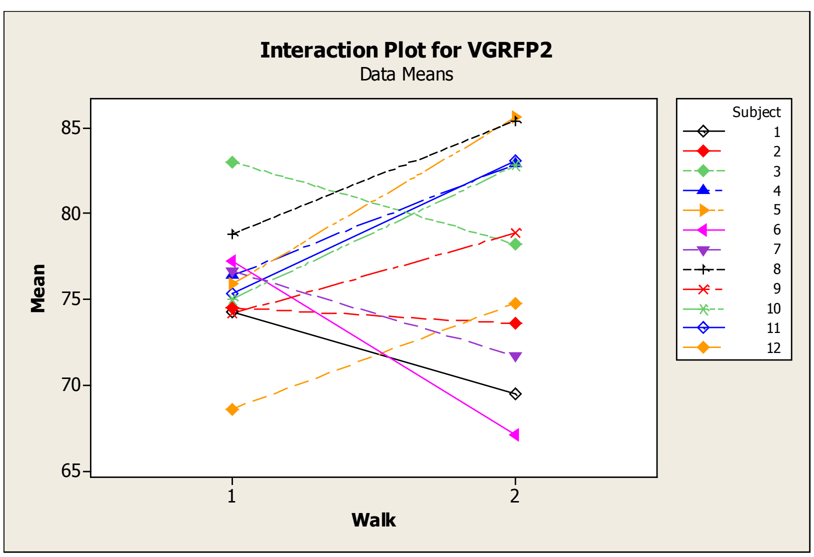


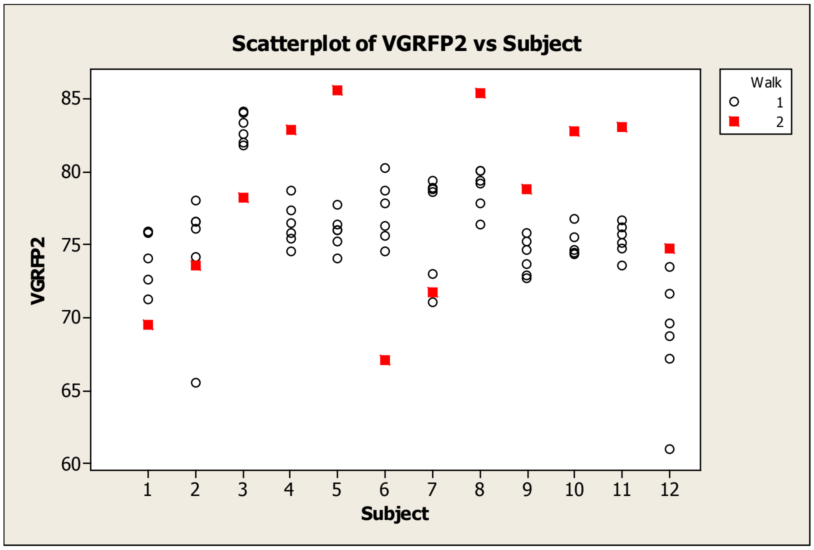
General Linear Model: VGRFP2 versus Subject, Walk

```
Factor    Type    Levels  Values
Subject   random      12  1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Walk      fixed        2  1, 2


Analysis of Variance for VGRFP2, using Adjusted SS for Tests

Source        DF    Seq SS   Adj SS  Adj MS     F      P
Subject       11   770.872  558.890  50.808  1.34  0.318
Walk           1    39.556   39.556  39.556  1.04  0.329
Subject*Walk  11   416.923  416.923  37.902  6.35  0.000
Error         60   358.395  358.395   5.973
Total         83  1585.745


S = 2.44402   R-Sq = 77.40%   R-Sq(adj) = 68.74%


Unusual Observations for VGRFP2

Obs   VGRFP2      Fit  SE Fit  Residual  St Resid
  7  69.4566  69.4566  2.4440    0.0000         * X
  9  65.5379  74.4957  0.9978   -8.9578     -4.02 R
 14  73.5702  73.5702  2.4440    0.0000         * X
 21  78.1973  78.1973  2.4440    0.0000         * X
 28  82.8455  82.8455  2.4440    0.0000         * X
 35  85.5580  85.5580  2.4440   -0.0000         * X
 42  67.0697  67.0697  2.4440    0.0000         * X
```

```
 44  71.0502  76.6348  0.9978  -5.5846     -2.50 R
 49  71.6915  71.6915  2.4440   0.0000         * X
 56  85.3905  85.3905  2.4440   0.0000         * X
 63  78.8373  78.8373  2.4440   0.0000         * X
 70  82.7673  82.7673  2.4440   0.0000         * X
 77  83.0122  83.0122  2.4440   0.0000         * X
 80  60.9945  68.5810  0.9978  -7.5866     -3.40 R
 83  73.4311  68.5810  0.9978   4.8501      2.17 R
 84  74.7610  74.7610  2.4440   0.0000         * X

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large leverage.

* WARNING * No multiple comparisons were calculated for the following terms
            which contain or interact with random factors.
Walk
```







MINITAB Results for General Linear Model: VGRFP3

General Linear Model: VGRFP3 versus Subject, Walk

Factor	Type	Levels	Values
Subject	random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Walk	fixed	2	1, 2

Analysis of Variance for VGRFP3, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	1602.52	1602.52	145.68	11.38	0.000
Walk	1	453.93	453.93	453.93	35.47	0.000
Error	71	908.56	908.56	12.80		
Total	83	2965.02				

S = 3.57724   R-Sq = 69.36%   R-Sq(adj) = 64.18%

Unusual Observations for VGRFP3

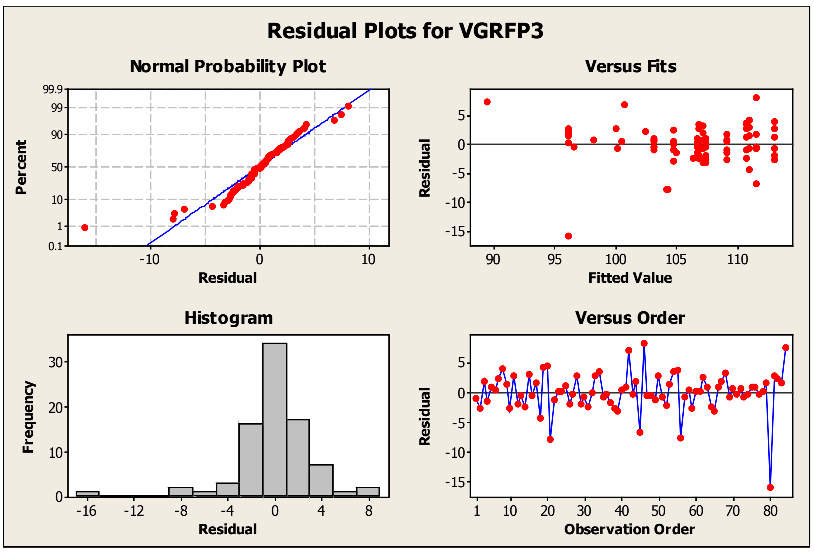
Obs	VGRFP3	Fit	SE Fit	Residual	St Resid	
21	96.414	104.373	1.656	-7.959	-2.51	R
42	107.671	100.773	1.656	6.898	2.18	R
45	104.780	111.611	1.361	-6.831	-2.06	R
46	119.781	111.611	1.361	8.170	2.47	R
56	96.385	104.159	1.656	-7.774	-2.45	R
80	80.140	96.140	1.361	-16.000	-4.84	R
84	97.023	89.497	1.656	7.526	2.37	R

R denotes an observation with a large standardized residual.

Grouping Information Using Tukey Method and 95.0% Confidence

Walk	N	Mean	Grouping
1	72	107.3	A

```
2      12  100.7     B

Means that do not share a letter are significantly different.


Tukey Simultaneous Tests
Response Variable VGRFP3
All Pairwise Comparisons among Levels of Walk
Walk = 1  subtracted from:

      Difference       SE of           Adjusted
Walk    of Means  Difference  T-Value   P-Value
2         -6.643       1.115   -5.956    0.0000
```



General Linear Model: VGRFP3 versus Subject, Walk

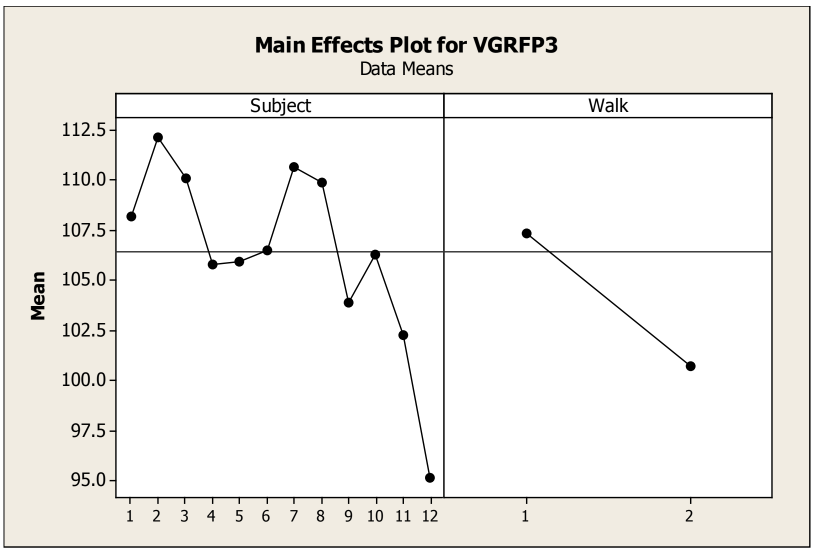
```
Factor   Type    Levels  Values
Subject  random      12  1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Walk     fixed        2  1, 2


Analysis of Variance for VGRFP3, using Adjusted SS for Tests

Source        DF   Seq SS  Adj SS  Adj MS      F      P
Subject       11  1602.52  484.14   44.01   1.66  0.206
Walk           1   453.93  453.93  453.93  17.15  0.002
Subject*Walk  11   291.11  291.11   26.46   2.57  0.010
Error         60   617.45  617.45   10.29
Total         83  2965.02


S = 3.20793   R-Sq = 79.18%   R-Sq(adj) = 71.19%


Unusual Observations for VGRFP3

Obs   VGRFP3      Fit  SE Fit  Residual  St Resid
  7  104.708  104.708   3.208     0.000         * X
 14  104.005  104.005   3.208     0.000         * X
 21   96.414   96.414   3.208     0.000         * X
```

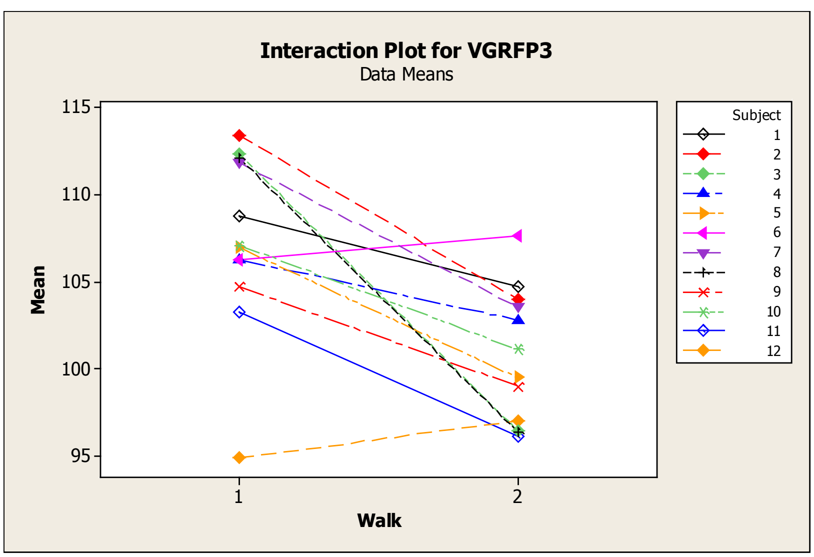
28	102.801	102.801	3.208	0.000	* X
35	99.498	99.498	3.208	0.000	* X
42	107.671	107.671	3.208	0.000	* X
45	104.780	111.847	1.310	-7.066	-2.41 R
46	119.781	111.847	1.310	7.935	2.71 R
49	103.557	103.557	3.208	0.000	* X
56	96.385	96.385	3.208	0.000	* X
63	99.000	99.000	3.208	0.000	* X
70	101.124	101.124	3.208	0.000	* X
77	96.143	96.143	3.208	0.000	* X
80	80.140	94.886	1.310	-14.745	-5.04 R
84	97.023	97.023	3.208	0.000	* X

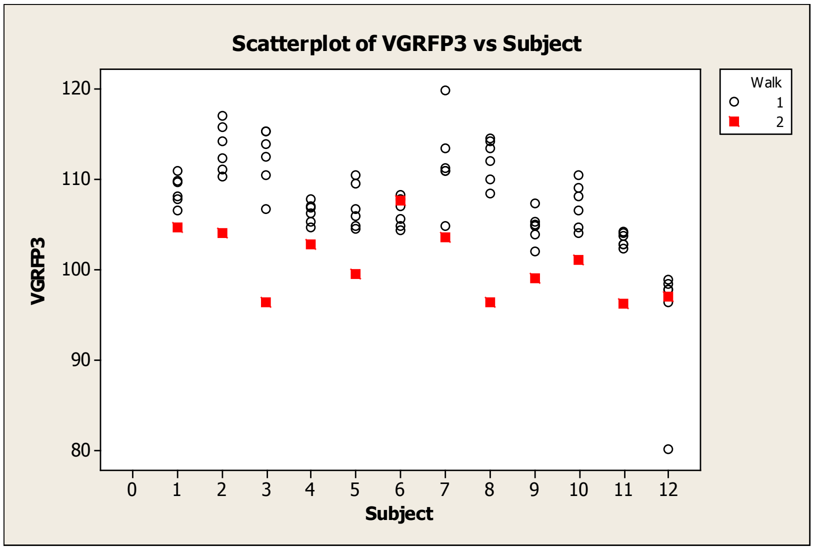
R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large leverage.

* WARNING * No multiple comparisons were calculated for the following terms which contain or interact with random factors.

Walk







MINITAB Results for General Linear Model: APGRFP1
General Linear Model: APGRFP1 versus Subject, Walk

Factor	Type	Levels	Values
Subject	random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Walk	fixed	2	1, 2

Analysis of Variance for APGRFP1, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	264.531	264.531	24.048	6.82	0.000
Walk	1	10.428	10.428	10.428	2.96	0.090
Error	71	250.441	250.441	3.527		
Total	83	525.400				

S = 1.87812   R-Sq = 52.33%   R-Sq(adj) = 44.28%

Unusual Observations for APGRFP1

Obs	APGRFP1	Fit	SE Fit	Residual	St Resid
21	14.2026	17.9564	0.8694	-3.7538	-2.25 R
28	12.0934	18.1326	0.8694	-6.0392	-3.63 R
35	11.4436	15.3853	0.8694	-3.9418	-2.37 R
42	19.5744	15.3687	0.8694	4.2058	2.53 R
45	20.4458	16.4013	0.7148	4.0445	2.33 R
46	12.2660	16.4013	0.7148	-4.1353	-2.38 R
77	16.4506	10.9835	0.8694	5.4671	3.28 R

R denotes an observation with a large standardized residual.

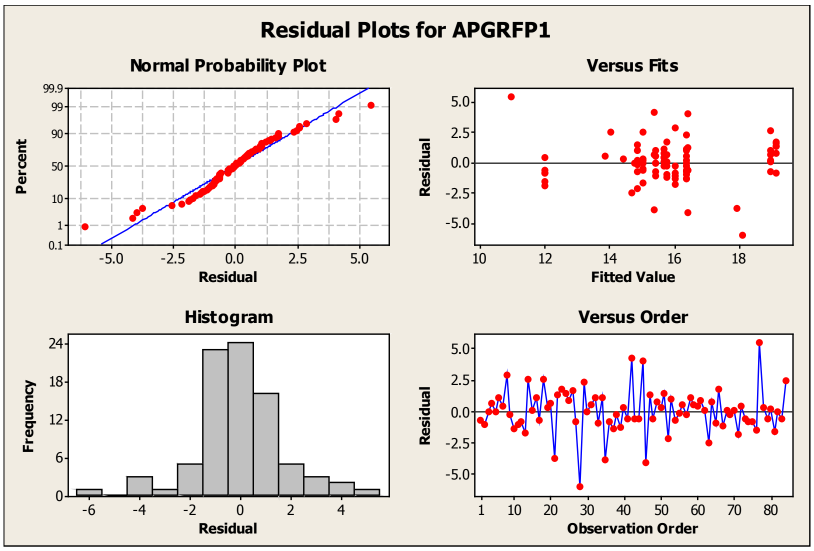
Grouping Information Using Tukey Method and 95.0% Confidence

Walk	N	Mean	Grouping
1	72	16.01	A
2	12	15.01	A

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests
Response Variable APGRFP1
All Pairwise Comparisons among Levels of Walk
Walk = 1 subtracted from:

Walk	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-1.007	0.5856	-1.719	0.0899



General Linear Model: APGRFP1 versus Subject, Walk

Factor	Type	Levels	Values
Subject	random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Walk	fixed	2	1, 2

Analysis of Variance for APGRFP1, using Adjusted SS for Tests

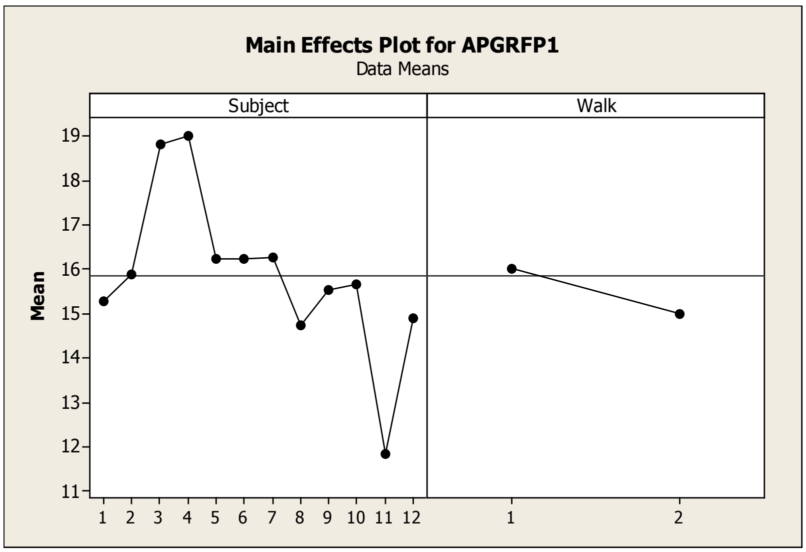
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	264.531	55.102	5.009	0.35	0.951
Walk	1	10.428	10.428	10.428	0.74	0.409
Subject*Walk	11	155.919	155.919	14.174	9.00	0.000
Error	60	94.523	94.523	1.575		
Total	83	525.400				

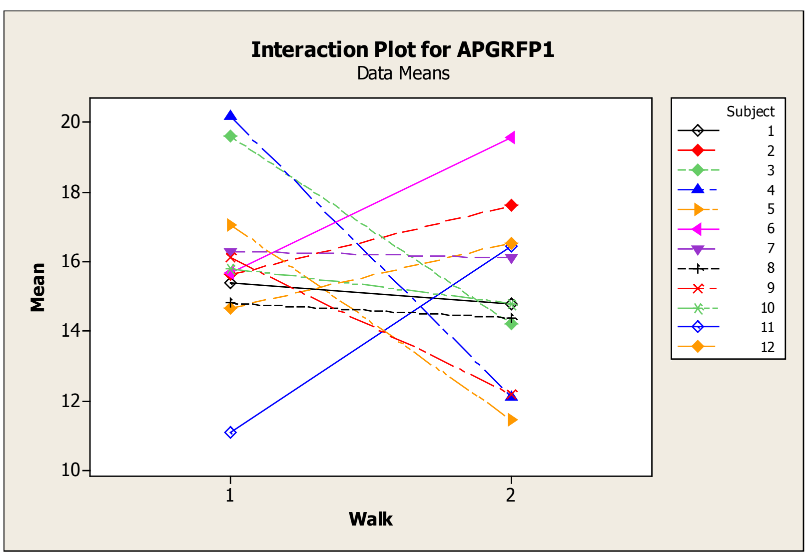
S = 1.25514 R-Sq = 82.01% R-Sq(adj) = 75.11%

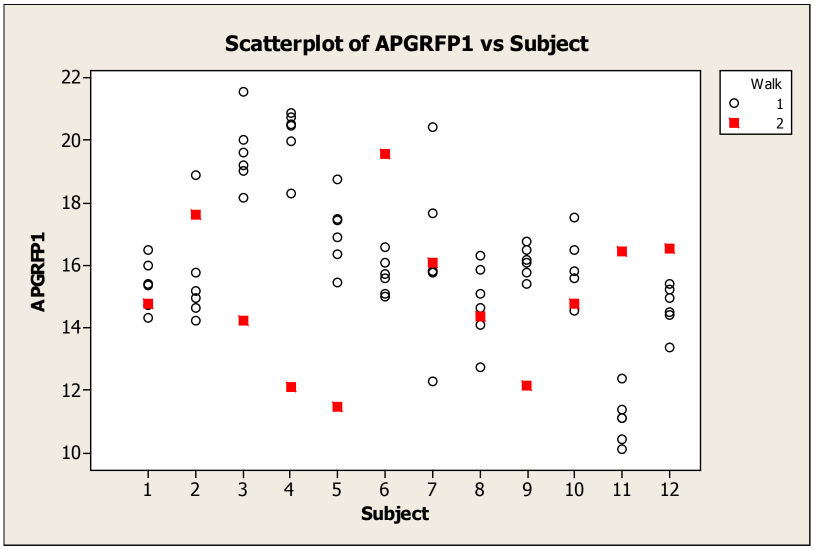
Unusual Observations for APGRFP1

Obs	APGRFP1	Fit	SE Fit	Residual	St Resid	
7	14.7713	14.7713	1.2551	0.0000	*	X
8	18.8966	15.6077	0.5124	3.2889	2.87	R
14	17.6009	17.6009	1.2551	-0.0000	*	X
21	14.2026	14.2026	1.2551	0.0000	*	X

```
 28  12.0934  12.0934  1.2551   -0.0000         * X
 35  11.4436  11.4436  1.2551    0.0000         * X
 42  19.5744  19.5744  1.2551    0.0000         * X
 45  20.4458  16.2851  0.5124    4.1607      3.63 R
 46  12.2660  16.2851  0.5124   -4.0191     -3.51 R
 49  16.0920  16.0920  1.2551   -0.0000         * X
 56  14.3640  14.3640  1.2551   -0.0000         * X
 63  12.1585  12.1585  1.2551   -0.0000         * X
 70  14.7840  14.7840  1.2551    0.0000         * X
 77  16.4506  16.4506  1.2551   -0.0000         * X
 84  16.5259  16.5259  1.2551   -0.0000         * X

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large leverage.

* WARNING * No multiple comparisons were calculated for the following terms
            which contain or interact with random factors.
Walk
```







MINITAB Results for General Linear Model: APGRFP2

General Linear Model: APGRFP2 versus Subject, Walk

Factor	Type	Levels	Values
Subject	random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Walk	fixed	2	1, 2

Analysis of Variance for APGRFP2, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	136.950	136.950	12.450	10.35	0.000
Walk	1	0.798	0.798	0.798	0.66	0.418
Error	71	85.445	85.445	1.203		
Total	83	223.192				

S = 1.09702   R-Sq = 61.72%   R-Sq(adj) = 55.25%

Unusual Observations for APGRFP2

Obs	APGRFP2	Fit	SE Fit	Residual	St Resid	
7	17.7127	20.5366	0.5078	-2.8240	-2.90	R
14	21.5519	19.0621	0.5078	2.4897	2.56	R
28	18.1914	21.0853	0.5078	-2.8940	-2.98	R
45	17.6471	19.6806	0.4175	-2.0335	-2.00	R
84	19.1515	16.2160	0.5078	2.9355	3.02	R

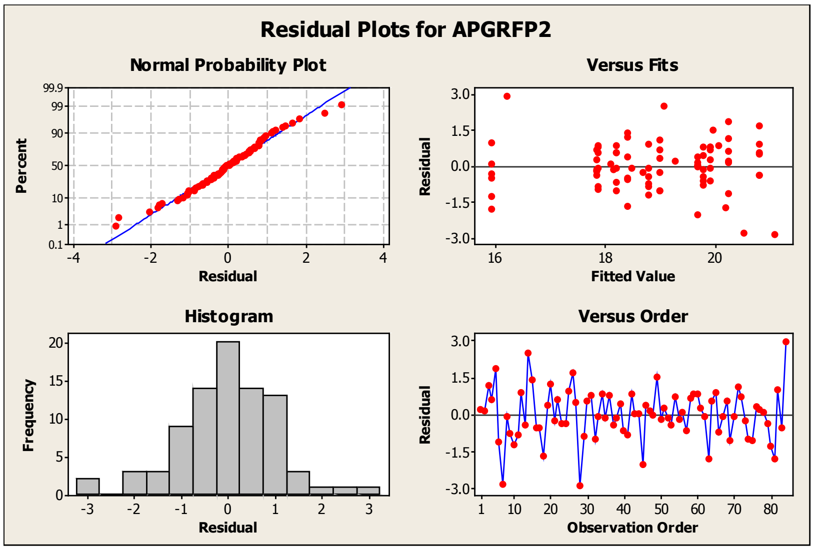
R denotes an observation with a large standardized residual.

Grouping Information Using Tukey Method and 95.0% Confidence

Walk	N	Mean	Grouping
2	12	19.15	A
1	72	18.87	A

Means that do not share a letter are significantly different.

```
Tukey Simultaneous Tests
Response Variable APGRFP2
All Pairwise Comparisons among Levels of Walk
Walk = 1  subtracted from:

      Difference       SE of              Adjusted
Walk    of Means  Difference  T-Value      P-Value
2         0.2785      0.3421   0.8141       0.4183
```



General Linear Model: APGRFP2 versus Subject, Walk

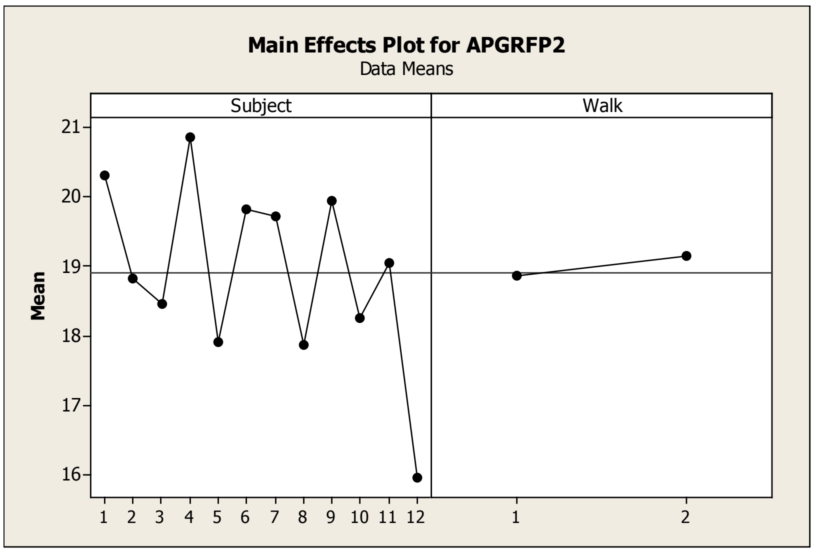
```
Factor   Type    Levels  Values
Subject  random      12  1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Walk     fixed        2  1, 2


Analysis of Variance for APGRFP2, using Adjusted SS for Tests

Source        DF    Seq SS   Adj SS  Adj MS     F      P
Subject       11  136.9503  38.0897  3.4627  0.87  0.588
Walk           1    0.7975   0.7975  0.7975  0.20  0.663
Subject*Walk  11   43.6640  43.6640  3.9695  5.70  0.000
Error         60   41.7806  41.7806  0.6963
Total         83  223.1923


S = 0.834472   R-Sq = 81.28%   R-Sq(adj) = 74.10%


Unusual Observations for APGRFP2

Obs  APGRFP2      Fit  SE Fit  Residual  St Resid
  6  19.1144  20.7288  0.3407   -1.6144     -2.12 R
  7  17.7127  17.7127  0.8345   -0.0000         * X
 14  21.5519  21.5519  0.8345    0.0000         * X
 18  16.7247  18.4625  0.3407   -1.7378     -2.28 R
 21  18.4485  18.4485  0.8345    0.0000         * X
 28  18.1914  18.1914  0.8345    0.0000         * X
```

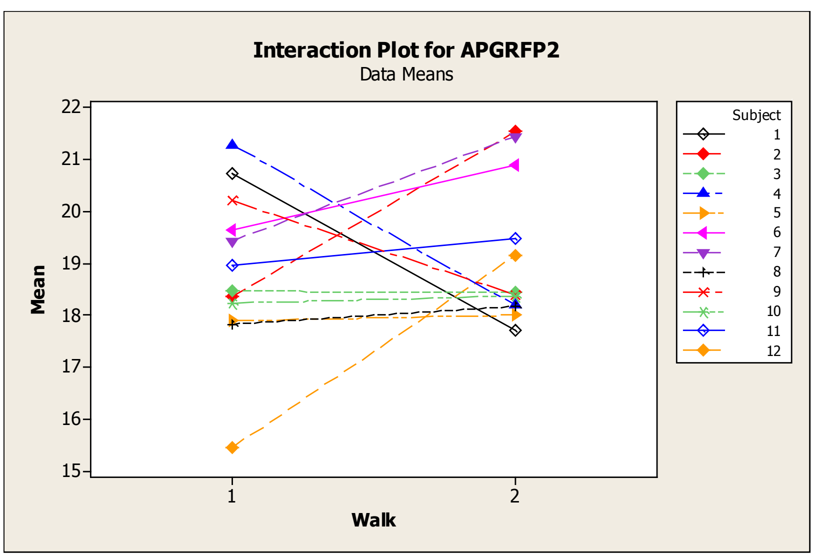
35	18.0017	18.0017	0.8345	0.0000	*	X
42	20.8858	20.8858	0.8345	0.0000	*	X
45	17.6471	19.4319	0.3407	-1.7848	-2.34	R
49	21.4512	21.4512	0.8345	-0.0000	*	X
56	18.1759	18.1759	0.8345	0.0000	*	X
63	18.3967	18.3967	0.8345	0.0000	*	X
70	18.3758	18.3758	0.8345	0.0000	*	X
77	19.4909	19.4909	0.8345	0.0000	*	X
84	19.1515	19.1515	0.8345	-0.0000	*	X

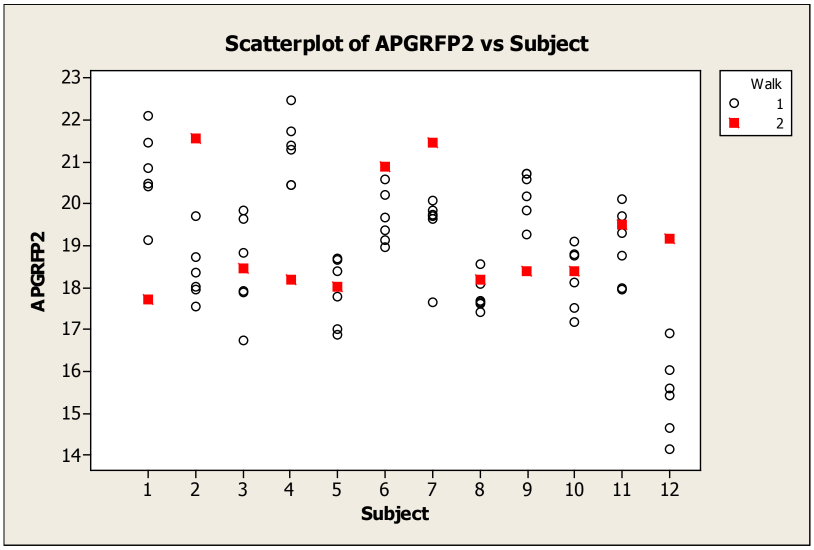
R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large leverage.

* WARNING * No multiple comparisons were calculated for the following terms
which contain or interact with random factors.

Walk



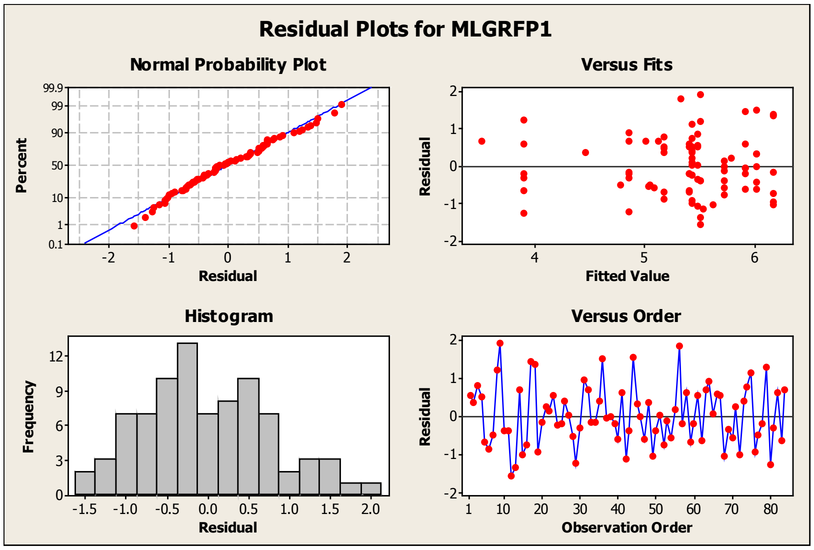




MINITAB Results for General Linear Model: MLGRFP1
General Linear Model: MLGRFP1 versus Subject, Walk

```
Factor    Type    Levels  Values
Subject   random      12  1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Walk      fixed        2  1, 2


Analysis of Variance for MLGRFP1, using Adjusted SS for Tests

Source   DF   Seq SS   Adj SS  Adj MS     F      P
Subject  11  27.8467  27.8467  2.5315  3.59  0.000
Walk      1   1.5766   1.5766  1.5766  2.24  0.139
Error    71  50.0081  50.0081  0.7043
Total    83  79.4313


S = 0.839249   R-Sq = 37.04%   R-Sq(adj) = 26.40%


Unusual Observations for MLGRFP1

Obs  MLGRFP1      Fit   SE Fit  Residual  St Resid
  9  7.41479  5.51425  0.31940   1.90053      2.45 R
 12  3.93518  5.51425  0.31940  -1.57907     -2.03 R
 56  7.13472  5.33747  0.38850   1.79726      2.42 R

R denotes an observation with a large standardized residual.


Grouping Information Using Tukey Method and 95.0% Confidence

Walk   N   Mean  Grouping
1     72  5.421  A
2     12  5.029  A

Means that do not share a letter are significantly different.
```

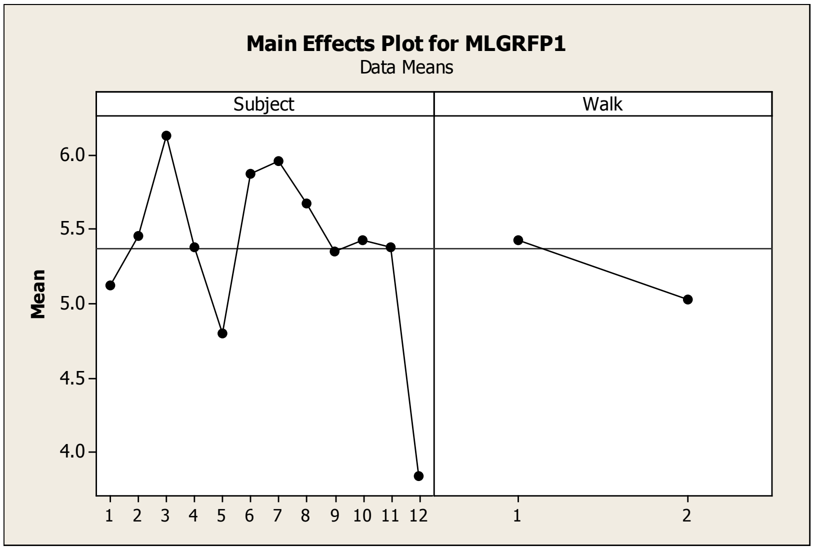
```
Tukey Simultaneous Tests
Response Variable MLGRFP1
All Pairwise Comparisons among Levels of Walk
Walk = 1  subtracted from:

      Difference       SE of             Adjusted
Walk    of Means  Difference  T-Value     P-Value
2        -0.3915      0.2617   -1.496      0.1391
```

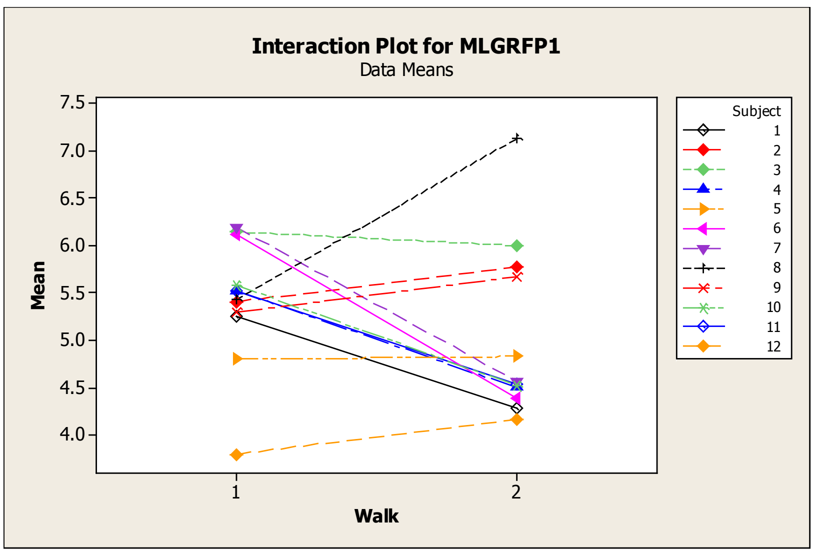


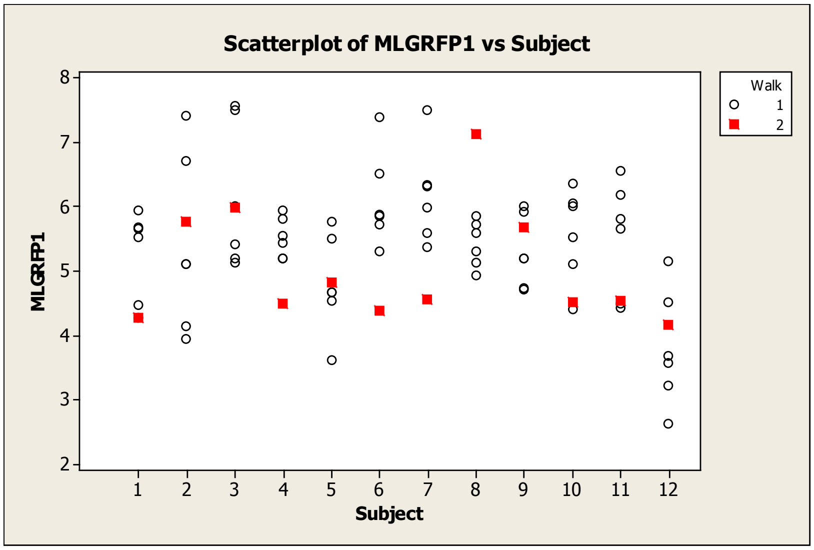
General Linear Model: MLGRFP1 versus Subject, Walk

```
Factor   Type    Levels  Values
Subject  random      12  1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Walk     fixed        2  1, 2


Analysis of Variance for MLGRFP1, using Adjusted SS for Tests

Source        DF   Seq SS   Adj SS  Adj MS     F      P
Subject       11  27.8467  14.0877  1.2807  1.46  0.270
Walk           1   1.5766   1.5766  1.5766  1.80  0.207
Subject*Walk  11   9.6473   9.6473  0.8770  1.30  0.245
Error         60  40.3608  40.3608  0.6727
Total         83  79.4313


S = 0.820171   R-Sq = 49.19%   R-Sq(adj) = 29.71%


Unusual Observations for MLGRFP1

Obs  MLGRFP1      Fit   SE Fit  Residual  St Resid
  7  4.28089  4.28089  0.82017  -0.00000         * X
  9  7.41479  5.40535  0.33483   2.00944      2.68 R
 14  5.77619  5.77619  0.82017   0.00000         * X
 21  5.99772  5.99772  0.82017   0.00000         * X
 28  4.49750  4.49750  0.82017  -0.00000         * X
 35  4.82772  4.82772  0.82017   0.00000         * X
 42  4.38573  4.38573  0.82017  -0.00000         * X
 49  4.56531  4.56531  0.82017  -0.00000         * X
```

```
 56  7.13472  7.13472  0.82017  -0.00000         * X
 63  5.67404  5.67404  0.82017   0.00000         * X
 70  4.51919  4.51919  0.82017   0.00000         * X
 77  4.53222  4.53222  0.82017   0.00000         * X
 84  4.16262  4.16262  0.82017   0.00000         * X

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large leverage.

* WARNING * No multiple comparisons were calculated for the following terms
            which contain or interact with random factors.
Walk
```







MINITAB Results for General Linear Model: MLGRFP2
General Linear Model: MLGRFP2 versus Subject, Walk

Factor	Type	Levels	Values
Subject	random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Walk	fixed	2	1, 2

Analysis of Variance for MLGRFP2, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	146.640	146.640	13.331	9.07	0.000
Walk	1	20.986	20.986	20.986	14.28	0.000
Error	71	104.371	104.371	1.470		
Total	83	271.997				

S = 1.21244   R-Sq = 61.63%   R-Sq(adj) = 55.14%

Unusual Observations for MLGRFP2

Obs	MLGRFP2	Fit	SE Fit	Residual	St Resid
21	6.57970	3.82090	0.56125	2.75880	2.57 R
35	2.71848	5.33478	0.56125	-2.61630	-2.43 R
56	6.94103	4.61015	0.56125	2.33088	2.17 R
63	5.29708	7.45721	0.56125	-2.16013	-2.01 R
80	2.43553	5.71737	0.46143	-3.28183	-2.93 R
84	8.15456	4.28897	0.56125	3.86559	3.60 R

R denotes an observation with a large standardized residual.

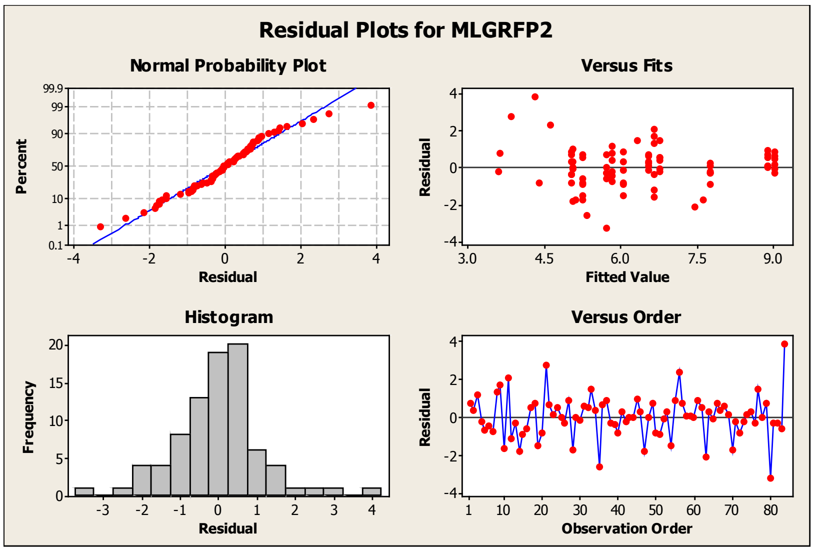
Grouping Information Using Tukey Method and 95.0% Confidence

Walk	N	Mean	Grouping
1	72	6.543	A
2	12	5.115	B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests
Response Variable MLGRFP2
All Pairwise Comparisons among Levels of Walk
Walk = 1 subtracted from:

Walk	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-1.428	0.3780	-3.778	0.0003



General Linear Model: MLGRFP2 versus Subject, Walk

Factor	Type	Levels	Values
Subject	random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Walk	fixed	2	1, 2

Analysis of Variance for MLGRFP2, using Adjusted SS for Tests

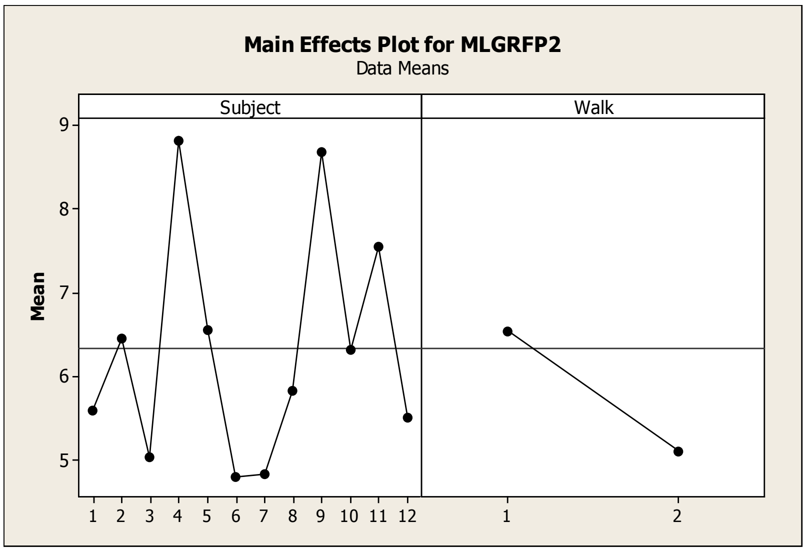
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	146.6398	55.7444	5.0677	0.92	0.556
Walk	1	20.9863	20.9863	20.9863	3.80	0.077
Subject*Walk	11	60.7865	60.7865	5.5260	7.61	0.000
Error	60	43.5849	43.5849	0.7264		
Total	83	271.9975				

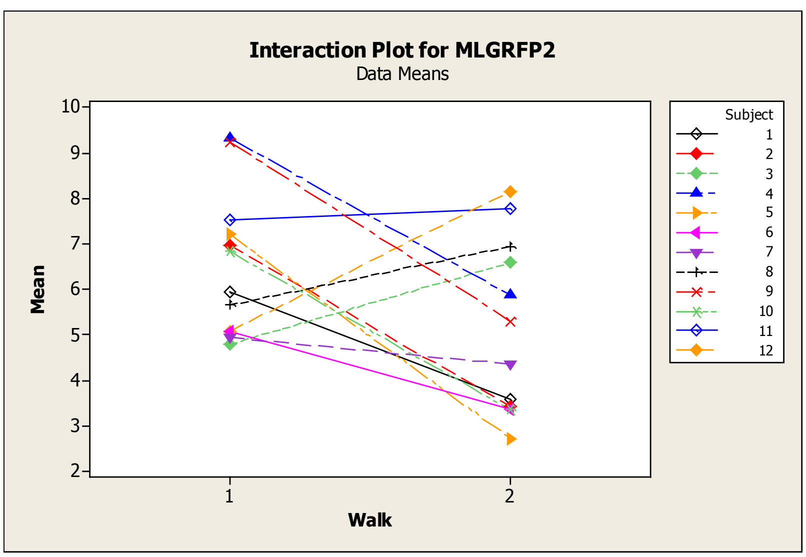
S = 0.852300 R-Sq = 83.98% R-Sq(adj) = 77.83%

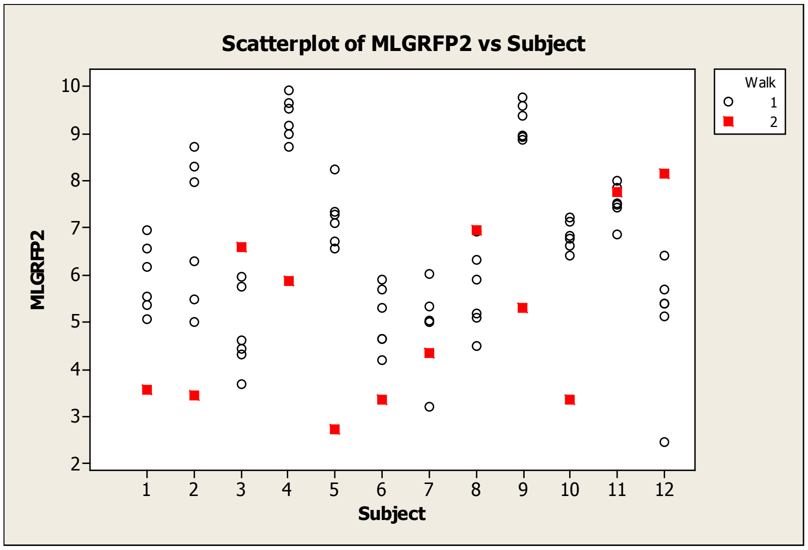
Unusual Observations for MLGRFP2

Obs	MLGRFP2	Fit	SE Fit	Residual	St Resid
7	3.57363	3.57363	0.85230	-0.00000	* X
10	5.01003	6.96023	0.34795	-1.95020	-2.51 R
11	8.70886	6.96023	0.34795	1.74863	2.25 R
14	3.42817	3.42817	0.85230	0.00000	* X

```
 21  6.57970  6.57970  0.85230  -0.00000         * X
 28  5.87385  5.87385  0.85230  -0.00000         * X
 35  2.71848  2.71848  0.85230   0.00000         * X
 42  3.35066  3.35066  0.85230  -0.00000         * X
 47  3.19879  4.92971  0.34795  -1.73092     -2.22 R
 49  4.35262  4.35262  0.85230   0.00000         * X
 56  6.94103  6.94103  0.85230  -0.00000         * X
 63  5.29708  5.29708  0.85230  -0.00000         * X
 70  3.35182  3.35182  0.85230   0.00000         * X
 77  7.75910  7.75910  0.85230  -0.00000         * X
 80  2.43553  5.07310  0.34795  -2.63757     -3.39 R
 84  8.15456  8.15456  0.85230   0.00000         * X

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large leverage.

* WARNING * No multiple comparisons were calculated for the following terms
            which contain or interact with random factors.
Walk
```







Scatterplot of MLGRFP2 vs Subject
MLGRFP2
Subject
Walk
1
2
10
9
8
7
6
5
4
3
2
1
2
3
4
5
6
7
8
9
10
11
12

Appendix E
Regression for Treadmill GRF Predictive Equations

Regression Analysis: VGRFP1_TM

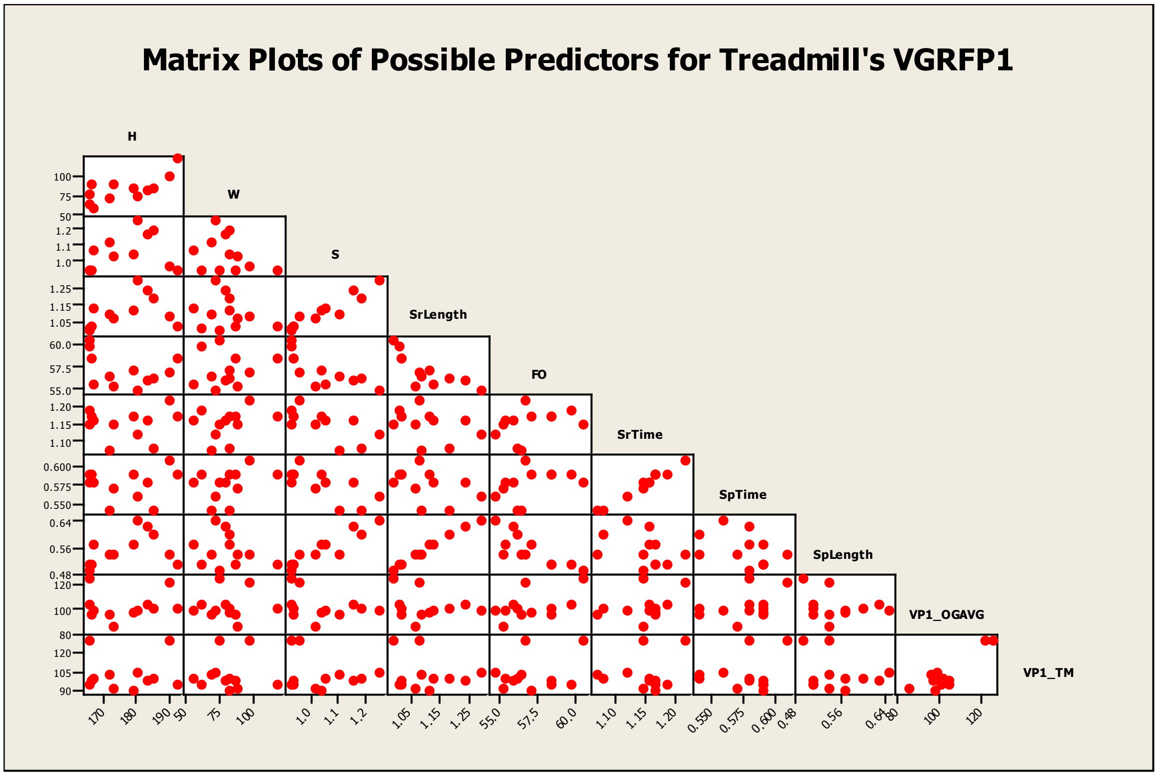
Correlations

		VGRFP1_TM	VGRFP1_OG	Height	Weight	Speed	StrideLength	FootOff	StrideTime	StepTime	StepLength
VGRFP1_TM	Pearson Correlation	1	.884**	.036	.033	-.222	-.195	.307	.194	.175	-.225
	Sig. (2-tailed)		.000	.911	.919	.489	.543	.331	.546	.587	.481
	N	12	12	12	12	12	12	12	12	12	12
VGRFP1_OG	Pearson Correlation	.884**	1	.118	.057	-.318	-.240	.531	.366	.383	-.250
	Sig. (2-tailed)	.000		.716	.861	.314	.452	.076	.242	.219	.433
	N	12	12	12	12	12	12	12	12	12	12
Height	Pearson Correlation	.036	.118	1	.727**	.269	.360	-.319	.104	.112	.376
	Sig. (2-tailed)	.911	.716		.007	.399	.251	.312	.747	.728	.228
	N	12	12	12	12	12	12	12	12	12	12
Weight	Pearson Correlation	.033	.057	.727**	1	-.295	-.239	.101	.299	.291	-.224
	Sig. (2-tailed)	.919	.861	.007		.352	.454	.756	.345	.358	.484
	N	12	12	12	12	12	12	12	12	12	12
Speed	Pearson Correlation	-.222	-.318	.269	-.295	1	.946**	-.764**	-.642*	-.620*	.930**
	Sig. (2-tailed)	.489	.314	.399	.352		.000	.004	.025	.031	.000
	N	12	12	12	12	12	12	12	12	12	12
StrideLength	Pearson Correlation	-.195	-.240	.360	-.239	.946**	1	-.796**	-.361	-.337	.997**
	Sig. (2-	.543	.452	.251	.454	.000		.002	.250	.283	.000

	tailed)										
	N	12	12	12	12	12	12	12	12	12	12
FootOff	Pearson Correlation	.307	.531	-.319	.101	-.764**	-.796**	1	.324	.358	-.794**
	Sig. (2-tailed)	.331	.076	.312	.756	.004	.002		.305	.254	.002
	N	12	12	12	12	12	12	12	12	12	12
StrideTime	Pearson Correlation	.194	.366	.104	.299	-.642*	-.361	.324	1	.991**	-.321
	Sig. (2-tailed)	.546	.242	.747	.345	.025	.250	.305		.000	.309
	N	12	12	12	12	12	12	12	12	12	12
StepTime	Pearson Correlation	.175	.383	.112	.291	-.620*	-.337	.358	.991**	1	-.294
	Sig. (2-tailed)	.587	.219	.728	.358	.031	.283	.254	.000		.354
	N	12	12	12	12	12	12	12	12	12	12
StepLength	Pearson Correlation	-.225	-.250	.376	-.224	.930**	.997**	-.794**	-.321	-.294	1
	Sig. (2-tailed)	.481	.433	.228	.484	.000	.000	.002	.309	.354	
	N	12	12	12	12	12	12	12	12	12	12

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).



Regression Analysis: VP1_TM versus VP1_OGAVG

```
The regression equation is
VP1_TM = - 11.2 + 1.11 VP1_OGAVG


Predictor     Coef   SE Coef      T      P
Constant    -11.19     19.23  -0.58  0.574
VP1_OGAVG   1.1125    0.1862   5.98  0.000


S = 6.81939   R-Sq = 78.1%   R-Sq(adj) = 75.9%


Analysis of Variance

Source          DF      SS      MS      F      P
Regression       1  1660.7  1660.7  35.71  0.000
Residual Error  10   465.0    46.5
Total           11  2125.8
```

Regression Analysis: VGRFP2_TM

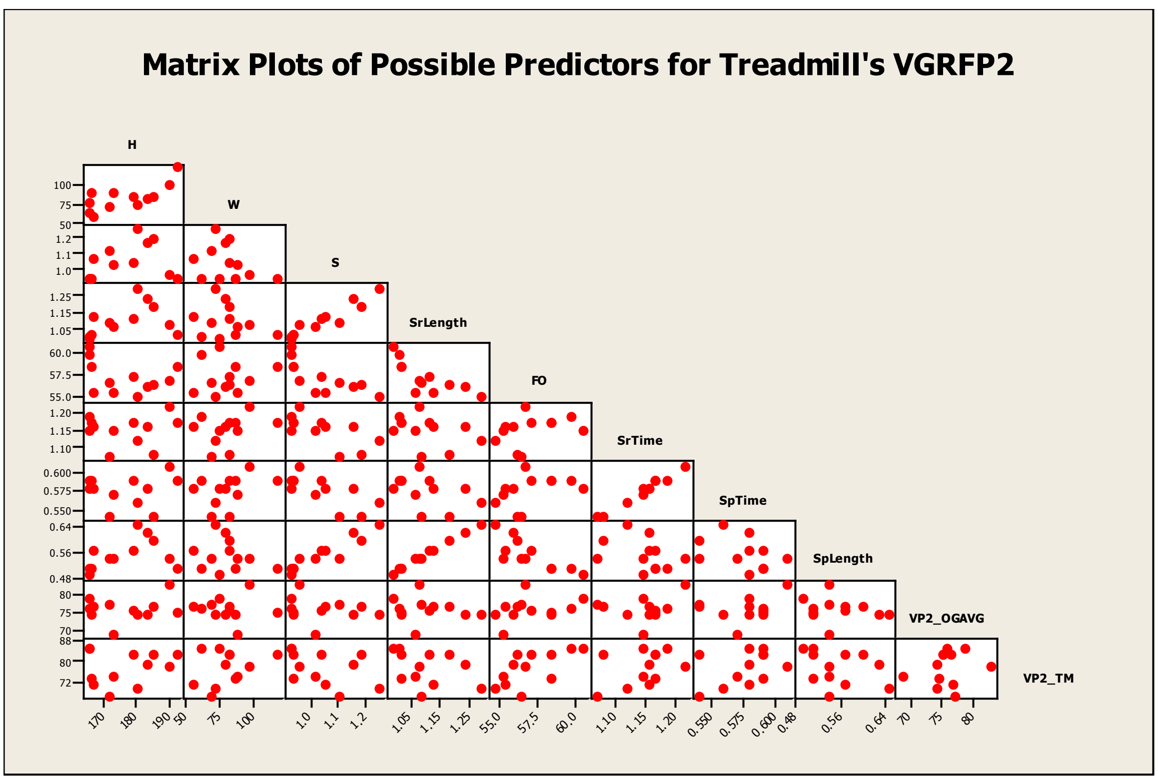
Correlations

		VGRFP2_TM	VGRFP2_OG	Height	Weight	Speed	StrideLength	FootOff	StrideTime	StepTime	StepLength
VGRFP2_TM	Pearson Correlation	1	.176	.168	.271	-.443	-.387	.657*	.372	.413	-.354
	Sig. (2-tailed)		.583	.602	.395	.149	.214	.020	.233	.182	.258
	N	12	12	12	12	12	12	12	12	12	12
VGRFP2_OG	Pearson Correlation	.176	1	.172	-.015	-.210	-.174	.322	.227	.244	-.179
	Sig. (2-tailed)	.583		.594	.962	.513	.589	.308	.478	.444	.579
	N	12	12	12	12	12	12	12	12	12	12
Height	Pearson Correlation	.168	.172	1	.727**	.269	.360	-.319	.104	.112	.376
	Sig. (2-tailed)	.602	.594		.007	.399	.251	.312	.747	.728	.228
	N	12	12	12	12	12	12	12	12	12	12
Weight	Pearson Correlation	.271	-.015	.727**	1	-.295	-.239	.101	.299	.291	-.224
	Sig. (2-tailed)	.395	.962	.007		.352	.454	.756	.345	.358	.484
	N	12	12	12	12	12	12	12	12	12	12
Speed	Pearson Correlation	-.443	-.210	.269	-.295	1	.946**	-.764**	-.642*	-.620*	.930**
	Sig. (2-tailed)	.149	.513	.399	.352		.000	.004	.025	.031	.000
	N	12	12	12	12	12	12	12	12	12	12
StrideLength	Pearson Correlation	-.387	-.174	.360	-.239	.946**	1	-.796**	-.361	-.337	.997**
	Sig. (2-tailed)	.214	.589	.251	.454	.000		.002	.250	.283	.000
	N	12	12	12	12	12	12	12	12	12	12
FootOff	Pearson Correlation	.657*	.322	-.319	.101	-.764**	-.796**	1	.324	.358	-.794**

	Sig. (2-tailed)	.020	.308	.312	.756	.004	.002		.305	.254	.002
	N	12	12	12	12	12	12	12	12	12	12
StrideTime	Pearson Correlation	.372	.227	.104	.299	-.642*	-.361	.324	1	.991**	-.321
	Sig. (2-tailed)	.233	.478	.747	.345	.025	.250	.305		.000	.309
	N	12	12	12	12	12	12	12	12	12	12
StepTime	Pearson Correlation	.413	.244	.112	.291	-.620*	-.337	.358	.991**	1	-.294
	Sig. (2-tailed)	.182	.444	.728	.358	.031	.283	.254	.000		.354
	N	12	12	12	12	12	12	12	12	12	12
StepLength	Pearson Correlation	-.354	-.179	.376	-.224	.930**	.997**	-.794**	-.321	-.294	1
	Sig. (2-tailed)	.258	.579	.228	.484	.000	.000	.002	.309	.354	
	N	12	12	12	12	12	12	12	12	12	12

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).



Regression Analysis: VP2_TM versus FO

```
The regression equation is
VP2_TM = - 49.2 + 2.23 FO


Predictor    Coef  SE Coef      T      P
Constant   -49.23    46.11  -1.07  0.311
FO         2.2253   0.8075   2.76  0.020


S = 5.03213   R-Sq = 43.2%   R-Sq(adj) = 37.5%


Analysis of Variance

Source          DF      SS      MS     F      P
Regression       1  192.29  192.29  7.59  0.020
Residual Error  10  253.22   25.32
Total           11  445.51
```

Regression Analysis: VGRFP3_TM

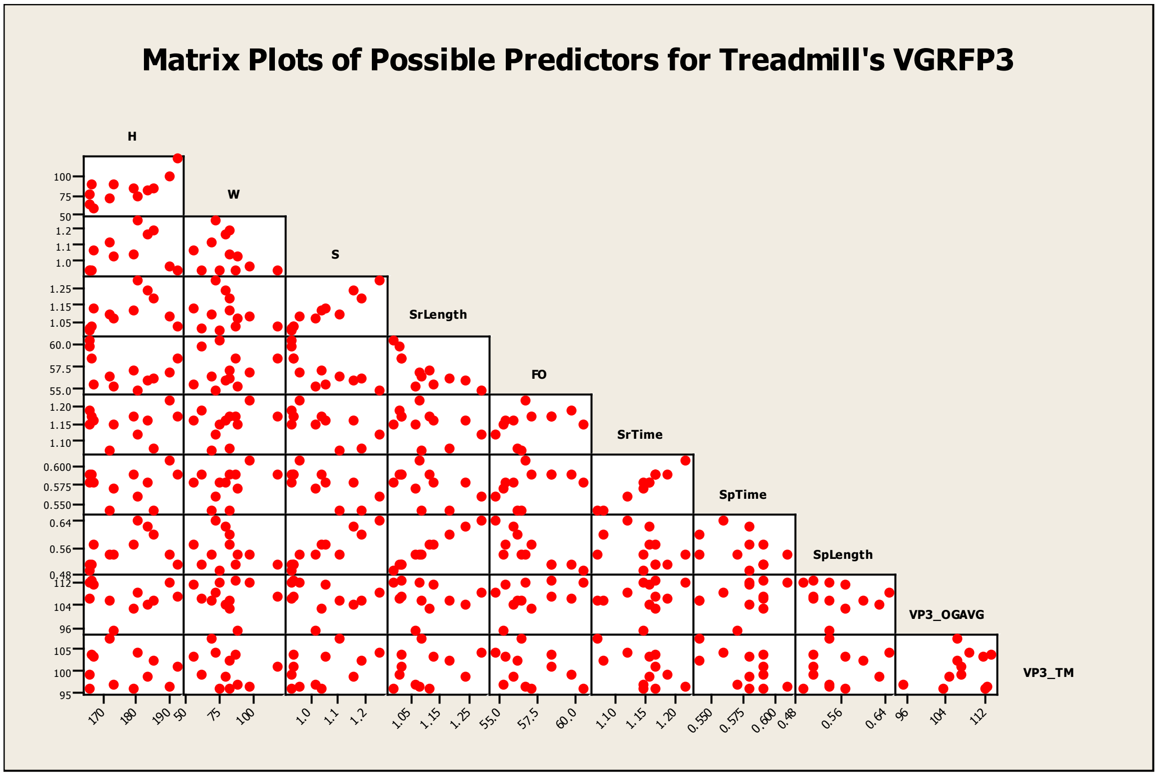
Correlations

		VGRFP3_TM	VGRFP3_OG	Height	Weight	Speed	StrideLength	Foot Off	Stride Time	StepTime	StepLength
VGRFP3_TM	Pearson Correlation	1	.259	-.151	-.286	.454	.281	-.307	-.635*	-.637*	.241
	Sig. (2-tailed)		.416	.638	.367	.138	.376	.332	.027	.026	.451
	N	12	12	12	12	12	12	12	12	12	12
VGRFP3_OG	Pearson Correlation	.259	1	-.131	-.131	-.201	-.159	.370	.225	.252	-.179
	Sig. (2-tailed)	.416		.684	.685	.531	.622	.236	.482	.430	.577
	N	12	12	12	12	12	12	12	12	12	12
Height	Pearson Correlation	-.151	-.131	1	.727**	.269	.360	-.319	.104	.112	.376
	Sig. (2-tailed)	.638	.684		.007	.399	.251	.312	.747	.728	.228
	N	12	12	12	12	12	12	12	12	12	12
Weight	Pearson Correlation	-.286	-.131	.727**	1	-.295	-.239	.101	.299	.291	-.224
	Sig. (2-tailed)	.367	.685	.007		.352	.454	.756	.345	.358	.484
	N	12	12	12	12	12	12	12	12	12	12

Speed	Pearson Correlation	.454	-.201	.269	-.295	1	.946**	-.764**	-.642*	-.620*	.930**
	Sig. (2-tailed)	.138	.531	.399	.352		.000	.004	.025	.031	.000
	N	12	12	12	12	12	12	12	12	12	12
StrideLength	Pearson Correlation	.281	-.159	.360	-.239	.946**	1	-.796**	-.361	-.337	.997**
	Sig. (2-tailed)	.376	.622	.251	.454	.000		.002	.250	.283	.000
	N	12	12	12	12	12	12	12	12	12	12
FootOff	Pearson Correlation	-.307	.370	-.319	.101	-.764**	-.796**	1	.324	.358	-.794**
	Sig. (2-tailed)	.332	.236	.312	.756	.004	.002		.305	.254	.002
	N	12	12	12	12	12	12	12	12	12	12
StrideTime	Pearson Correlation	-.635*	.225	.104	.299	-.642*	-.361	.324	1	.991**	-.321
	Sig. (2-tailed)	.027	.482	.747	.345	.025	.250	.305		.000	.309
	N	12	12	12	12	12	12	12	12	12	12
StepTime	Pearson Correlation	-.637*	.252	.112	.291	-.620*	-.337	.358	.991**	1	-.294
	Sig. (2-tailed)	.026	.430	.728	.358	.031	.283	.254	.000		.354
	N	12	12	12	12	12	12	12	12	12	12
StepLength	Pearson Correlation	.241	-.179	.376	-.224	.930**	.997**	-.794**	-.321	-.294	1
	Sig. (2-tailed)	.451	.577	.228	.484	.000	.000	.002	.309	.354	
	N	12	12	12	12	12	12	12	12	12	12

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).



Regression Analysis: VP3_TM versus VP3_OGAVG, SpTime

```
The regression equation is
VP3_TM = 142 + 0.363 VP3_OGAVG - 140 SpTime


Predictor       Coef  SE Coef      T      P
Constant      142.40    24.96   5.70  0.000
VP3_OGAVG     0.3627   0.1666   2.18  0.057
SpTime       -139.83    40.54  -3.45  0.007


S = 2.70537   R-Sq = 59.8%   R-Sq(adj) = 50.9%


Analysis of Variance

Source          DF       SS      MS     F      P
Regression       2   98.077  49.039  6.70  0.017
Residual Error   9   65.871   7.319
Total           11  163.949


Source     DF  Seq SS
VP3_OGAVG   1  10.995
SpTime      1  87.083
```

Regression Analysis: APGRFP1_TM

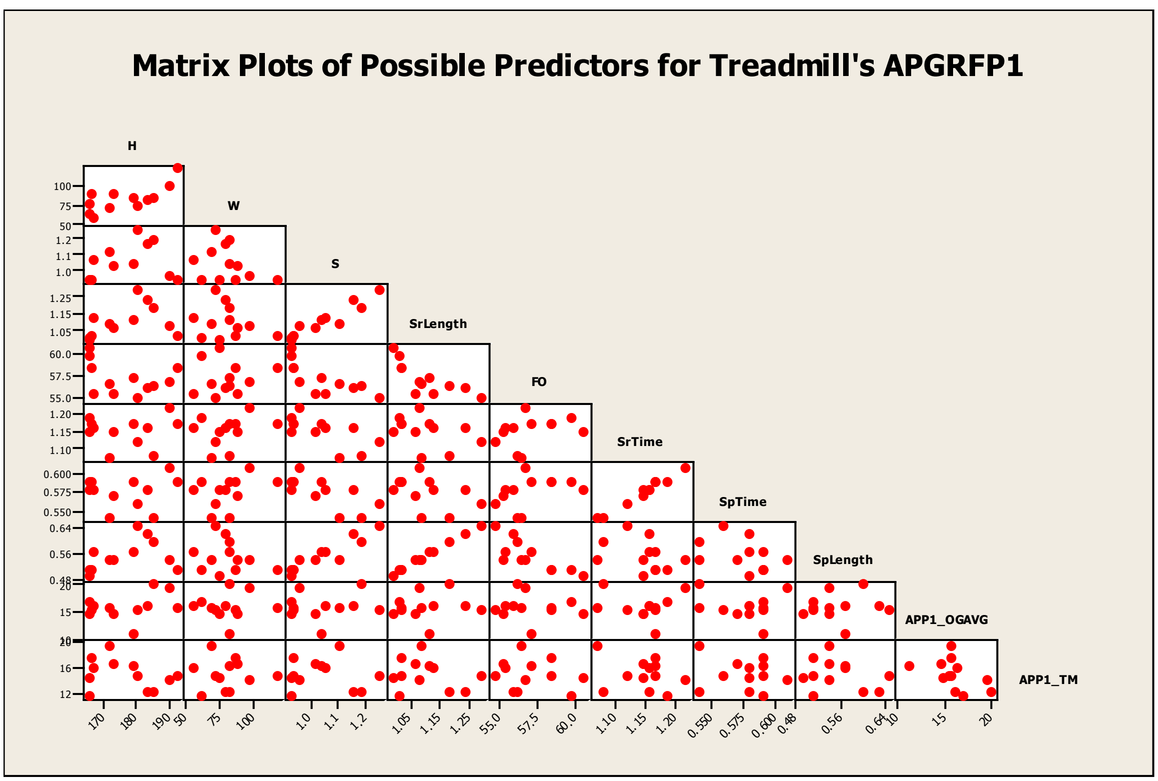
Correlations

		APGRFP1_TM	APGRFP1_OG	Height	Weight	Speed	StrideLength	FootOff	StrideTime	StepTime	StepLength
APGRFP1_TM	Pearson Correlation	1	-.478	-.289	.000	-.081	-.193	-.193	-.250	-.252	-.202
	Sig. (2-tailed)		.116	.361	.999	.803	.547	.548	.434	.429	.529
	N	12	12	12	12	12	12	12	12	12	12
APGRFP1_OG	Pearson Correlation	-.478	1	.305	.067	.110	.088	-.075	-.059	-.130	.060
	Sig. (2-tailed)	.116		.334	.835	.733	.786	.818	.854	.688	.853
	N	12	12	12	12	12	12	12	12	12	12
Height	Pearson Correlation	-.289	.305	1	.727**	.269	.360	-.319	.104	.112	.376
	Sig. (2-tailed)	.361	.334		.007	.399	.251	.312	.747	.728	.228
	N	12	12	12	12	12	12	12	12	12	12
Weight	Pearson Correlation	.000	.067	.727**	1	-.295	-.239	.101	.299	.291	-.224
	Sig. (2-tailed)	.999	.835	.007		.352	.454	.756	.345	.358	.484
	N	12	12	12	12	12	12	12	12	12	12
Speed	Pearson Correlation	-.081	.110	.269	-.295	1	.946**	-.764**	-.642*	-.620*	.930**
	Sig. (2-tailed)	.803	.733	.399	.352		.000	.004	.025	.031	.000
	N	12	12	12	12	12	12	12	12	12	12
StrideLength	Pearson Correlation	-.193	.088	.360	-.239	.946**	1	-.796**	-.361	-.337	.997**
	Sig. (2-tailed)	.547	.786	.251	.454	.000		.002	.250	.283	.000
	N	12	12	12	12	12	12	12	12	12	12
FootOff	Pearson Correlation	-.193	-.075	-.319	.101	-.764**	-.796**	1	.324	.358	-.794**

	Sig. (2-tailed)	.548	.818	.312	.756	.004	.002		.305	.254	.002
	N	12	12	12	12	12	12	12	12	12	12
StrideTime	Pearson Correlation	-.250	-.059	.104	.299	-.642*	-.361	.324	1	.991**	-.321
	Sig. (2-tailed)	.434	.854	.747	.345	.025	.250	.305		.000	.309
	N	12	12	12	12	12	12	12	12	12	12
StepTime	Pearson Correlation	-.252	-.130	.112	.291	-.620*	-.337	.358	.991**	1	-.294
	Sig. (2-tailed)	.429	.688	.728	.358	.031	.283	.254	.000		.354
	N	12	12	12	12	12	12	12	12	12	12
StepLength	Pearson Correlation	-.202	.060	.376	-.224	.930**	.997**	-.794**	-.321	-.294	1
	Sig. (2-tailed)	.529	.853	.228	.484	.000	.000	.002	.309	.354	
	N	12	12	12	12	12	12	12	12	12	12

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).



Regression Analysis: APP1_TM versus FO, SpLength

```
The regression equation is
APP1_TM = 113 - 1.25 FO - 47.7 SpLength


Predictor      Coef  SE Coef      T      P
Constant     113.06    38.86   2.91  0.017
FO          -1.2541   0.5225  -2.40  0.040
SpLength     -47.72    19.42  -2.46  0.036


S = 2.01847   R-Sq = 42.4%   R-Sq(adj) = 29.6%


Analysis of Variance

Source          DF      SS      MS     F      P
Regression       2  26.957  13.478  3.31  0.084
Residual Error   9  36.668   4.074
Total           11  63.625


Source    DF  Seq SS
FO         1   2.366
SpLength   1  24.590
```

Regression Analysis: APGRFP2_TM

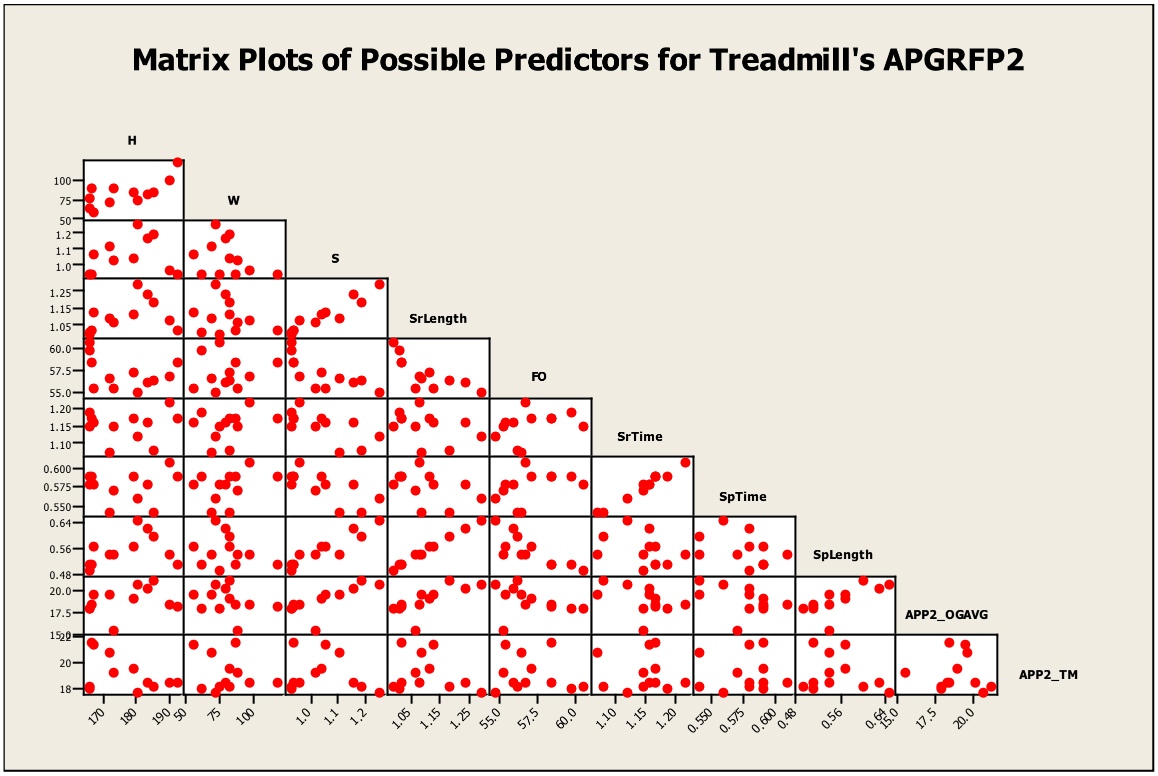
Correlations

		APGRFP2_TM	APGRFP2_OG	Height	Weight	Speed	StrideLength	Foot Off	Stride Time	Step Time	StepLength
APGRFP2_TM	Pearson Correlation	1	-.069	-.483	-.258	-.145	-.212	-.140	-.107	-.111	-.211
	Sig. (2-tailed)		.832	.112	.417	.653	.508	.663	.741	.730	.510
	N	12	12	12	12	12	12	12	12	12	12
APGRFP2_OG	Pearson Correlation	-.069	1	.309	-.251	.747**	.709**	-.349	-.456	-.391	.700*
	Sig. (2-tailed)	.832		.328	.431	.005	.010	.266	.136	.209	.011
	N	12	12	12	12	12	12	12	12	12	12
Height	Pearson Correlation	-.483	.309	1	.727**	.269	.360	-.319	.104	.112	.376
	Sig. (2-tailed)	.112	.328		.007	.399	.251	.312	.747	.728	.228
	N	12	12	12	12	12	12	12	12	12	12
Weight	Pearson Correl	-.258	-.251	.727**	1	-.295	-.239	.101	.299	.291	-.224

	ation										
	Sig. (2-tailed)	.417	.431	.007		.352	.454	.756	.345	.358	.484
	N	12	12	12	12	12	12	12	12	12	12
Speed	Pearson Correlation	-.145	.747**	.269	-.295	1	.946**	-.764**	-.642*	-.620*	.930**
	Sig. (2-tailed)	.653	.005	.399	.352		.000	.004	.025	.031	.000
	N	12	12	12	12	12	12	12	12	12	12
StrideLength	Pearson Correlation	-.212	.709**	.360	-.239	.946**	1	-.796**	-.361	-.337	.997**
	Sig. (2-tailed)	.508	.010	.251	.454	.000		.002	.250	.283	.000
	N	12	12	12	12	12	12	12	12	12	12
FootOff	Pearson Correlation	-.140	-.349	-.319	.101	-.764**	-.796**	1	.324	.358	-.794**
	Sig. (2-tailed)	.663	.266	.312	.756	.004	.002		.305	.254	.002
	N	12	12	12	12	12	12	12	12	12	12
StrideTime	Pearson Correlation	-.107	-.456	.104	.299	-.642*	-.361	.324	1	.991**	-.321
	Sig. (2-tailed)	.741	.136	.747	.345	.025	.250	.305		.000	.309
	N	12	12	12	12	12	12	12	12	12	12
StepTime	Pearson Correlation	-.111	-.391	.112	.291	-.620*	-.337	.358	.991**	1	-.294
	Sig. (2-tailed)	.730	.209	.728	.358	.031	.283	.254	.000		.354
	N	12	12	12	12	12	12	12	12	12	12
StepLength	Pearson Correlation	-.211	.700*	.376	-.224	.930**	.997**	-.794**	-.321	-.294	1
	Sig. (2-tailed)	.510	.011	.228	.484	.000	.000	.002	.309	.354	
	N	12	12	12	12	12	12	12	12	12	12

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).



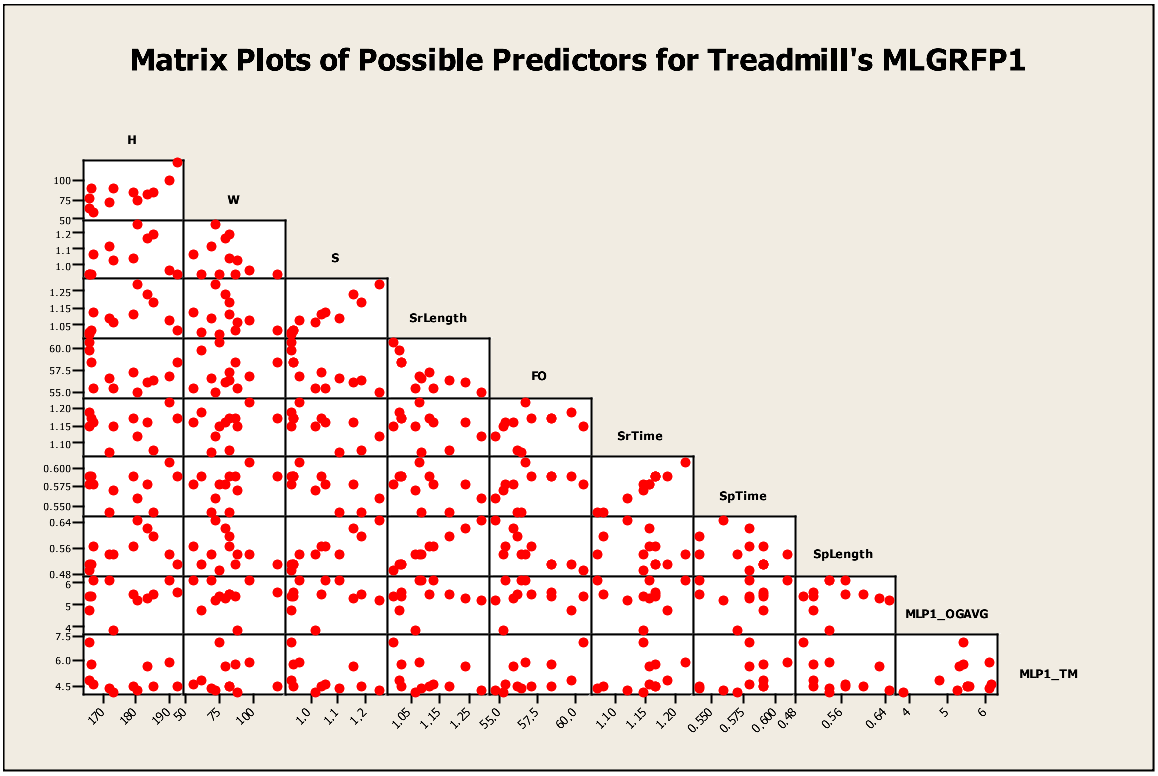
Regression Analysis: MLGRFP1_TM

Correlations

		MLGRFP1_TM	MLGRFP1_OG	Height	Weight	Speed	StrideLength	Foot Off	Stride Time	Step Time	StepLength
MLGRFP1_TM	Pearson Correlation	1	.197	-.174	.040	-.444	-.375	.601*	.388	.407	-.386
	Sig. (2-tailed)		.539	.588	.901	.148	.230	.039	.212	.189	.215
	N	12	12	12	12	12	12	12	12	12	12
MLGRFP1_OG	Pearson Correlation	.197	1	.197	-.061	.079	.072	.000	-.041	.004	.067
	Sig. (2-tailed)	.539		.540	.850	.808	.824	.999	.899	.991	.837
	N	12	12	12	12	12	12	12	12	12	12
Height	Pearson Correlation	-.174	.197	1	.727**	.269	.360	-.319	.104	.112	.376
	Sig. (2-tailed)	.588	.540		.007	.399	.251	.312	.747	.728	.228
	N	12	12	12	12	12	12	12	12	12	12

Weight	Pearson Correlation	.040	-.061	.727**	1	-.295	-.239	.101	.299	.291	-.224
	Sig. (2-tailed)	.901	.850	.007		.352	.454	.756	.345	.358	.484
	N	12	12	12	12	12	12	12	12	12	12
Speed	Pearson Correlation	-.444	.079	.269	-.295	1	.946**	-.764**	-.642*	-.620*	.930**
	Sig. (2-tailed)	.148	.808	.399	.352		.000	.004	.025	.031	.000
	N	12	12	12	12	12	12	12	12	12	12
StrideLength	Pearson Correlation	-.375	.072	.360	-.239	.946**	1	-.796**	-.361	-.337	.997**
	Sig. (2-tailed)	.230	.824	.251	.454	.000		.002	.250	.283	.000
	N	12	12	12	12	12	12	12	12	12	12
FootOff	Pearson Correlation	.601*	.000	-.319	.101	-.764**	-.796**	1	.324	.358	-.794**
	Sig. (2-tailed)	.039	.999	.312	.756	.004	.002		.305	.254	.002
	N	12	12	12	12	12	12	12	12	12	12
StrideTime	Pearson Correlation	.388	-.041	.104	.299	-.642*	-.361	.324	1	.991**	-.321
	Sig. (2-tailed)	.212	.899	.747	.345	.025	.250	.305		.000	.309
	N	12	12	12	12	12	12	12	12	12	12
StepTime	Pearson Correlation	.407	.004	.112	.291	-.620*	-.337	.358	.991**	1	-.294
	Sig. (2-tailed)	.189	.991	.728	.358	.031	.283	.254	.000		.354
	N	12	12	12	12	12	12	12	12	12	12
StepLength	Pearson Correlation	-.386	.067	.376	-.224	.930**	.997**	-.794**	-.321	-.294	1
	Sig. (2-tailed)	.215	.837	.228	.484	.000	.000	.002	.309	.354	
	N	12	12	12	12	12	12	12	12	12	12

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed).



Regression Analysis: MLP1_TM versus FO

```
The regression equation is
MLP1_TM = - 11.6 + 0.292 FO


Predictor      Coef  SE Coef      T      P
Constant    -11.614    6.986  -1.66  0.127
FO           0.2916   0.1224   2.38  0.038


S = 0.762431   R-Sq = 36.2%   R-Sq(adj) = 29.9%


Analysis of Variance

Source          DF      SS      MS     F      P
Regression       1  3.3026  3.3026  5.68  0.038
Residual Error  10  5.8130  0.5813
Total           11  9.1157
```

Regression Analysis: MLGRFP2_TM

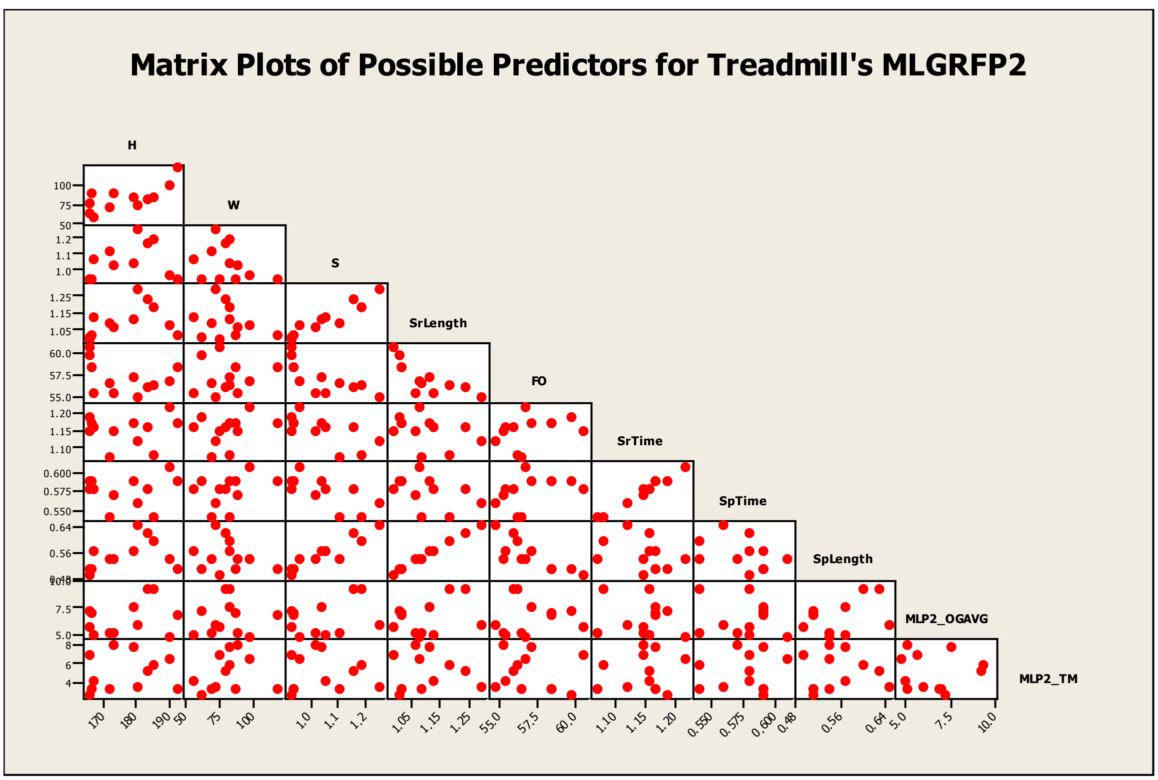
Correlations

		MLGRFP2_TM	MLGRFP2_OG	Height	Weight	Speed	StrideLength	FootOff	StrideTime	StepTime	StepLength
MLGRFP2_TM	Pearson Correlation	1	-.044	.141	.178	-.042	.007	-.141	.122	.118	.035
	Sig. (2-tailed)		.892	.662	.579	.896	.983	.662	.705	.714	.913
	N	12	12	12	12	12	12	12	12	12	12
MLGRFP2_OG	Pearson Correlation	-.044	1	.290	.096	.306	.314	.065	-.134	-.065	.340
	Sig. (2-tailed)	.892		.360	.766	.333	.320	.842	.678	.841	.279
	N	12	12	12	12	12	12	12	12	12	12
Height	Pearson Correlation	.141	.290	1	.727**	.269	.360	-.319	.104	.112	.376
	Sig. (2-tailed)	.662	.360		.007	.399	.251	.312	.747	.728	.228
	N	12	12	12	12	12	12	12	12	12	12
Weight	Pearson Correlation	.178	.096	.727**	1	-.295	-.239	.101	.299	.291	-.224
	Sig. (2-tailed)	.579	.766	.007		.352	.454	.756	.345	.358	.484
	N	12	12	12	12	12	12	12	12	12	12
Speed	Pearson Correlation	-.042	.306	.269	-.295	1	.946**	-.764**	-.642*	-.620*	.930**
	Sig. (2-tailed)	.896	.333	.399	.352		.000	.004	.025	.031	.000
	N	12	12	12	12	12	12	12	12	12	12
StrideLength	Pearson Correlation	.007	.314	.360	-.239	.946**	1	-.796**	-.361	-.337	.997**
	Sig. (2-tailed)	.983	.320	.251	.454	.000		.002	.250	.283	.000
	N	12	12	12	12	12	12	12	12	12	12
FootOff	Pearson Correlation	-.141	.065	-.319	.101	-.764**	-.796**	1	.324	.358	-.794**

	Sig. (2-tailed)	.662	.842	.312	.756	.004	.002		.305	.254	.002
	N	12	12	12	12	12	12	12	12	12	12
StrideTime	Pearson Correlation	.122	-.134	.104	.299	-.642*	-.361	.324	1	.991**	-.321
	Sig. (2-tailed)	.705	.678	.747	.345	.025	.250	.305		.000	.309
	N	12	12	12	12	12	12	12	12	12	12
StepTime	Pearson Correlation	.118	-.065	.112	.291	-.620*	-.337	.358	.991**	1	-.294
	Sig. (2-tailed)	.714	.841	.728	.358	.031	.283	.254	.000		.354
	N	12	12	12	12	12	12	12	12	12	12
StepLength	Pearson Correlation	.035	.340	.376	-.224	.930**	.997**	-.794**	-.321	-.294	1
	Sig. (2-tailed)	.913	.279	.228	.484	.000	.000	.002	.309	.354	
	N	12	12	12	12	12	12	12	12	12	12

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).



References

Adelson, W., J. A. Yaggie, et al. (2005). "The vertical component of the ground reaction force and running economy." Clinical Kinesiology. American Kinesiotherapy Association. 2005. **Spring**.

Alton, F., L. Baldey, et al. (1998). "A kinematic comparison of overground and treadmill walking." Clin Biomech (Bristol, Avon) **13**(6): 434-440.

Belli, A., P. Bui, et al. (2001). "A treadmill ergometer for three-dimensional ground reaction forces measurement during walking." J Biomech **34**(1): 105-112.

Buczek, F. L. and P. R. Cavanagh (1990). "Stance phase knee and ankle kinematics and kinetics during level and downhill running." Med Sci Sports Exerc **22**(5): 669-677.

Cavanagh, P. R. and M. A. Lafortune (1980). "Ground reaction forces in distance running." J Biomech **13**(5): 397-406.

Chatterjee, S. and A. S. Hadi (2006). Regression Analysis By Example. Hoboken, N.J., Wiley-Interscience.

Davis, B. L. and P. R. Cavanagh (1993). "Decomposition of superimposed ground reaction forces into left and right force profiles." J Biomech **26**(4-5): 593-597.

Dierick, F., M. Penta, et al. (2004). "A force measuring treadmill in clinical gait analysis." Gait Posture **20**(3): 299-303.

Dingwell, J. B., J. P. Cusumano, et al. (2001). "Local dynamic stability versus kinematic variability of continuous overground and treadmill walking." J Biomech Eng **123**(1): 27-32.

Durward, B. R., G. D. Baer, et al. (1999). Functional Human Movement: Measurement and Analysis. Oxford ; Boston, Mass, Butterworth-Heinemann.

Elvin, N. G., A. A. Elvin, et al. (2007). "Correlation between ground reaction force and tibial acceleration in vertical jumping." J Appl Biomech **23**(3): 180-189.

Fellin, R. E., K. Manal, et al. (2010). "Comparison of lower extremity kinematic curves during overground and treadmill running." J Appl Biomech **26**(4): 407-414.

Forner Cordero, A., H. J. Koopman, et al. (2004). "Use of pressure insoles to calculate the complete ground reaction forces." J Biomech **37**(9): 1427-1432.

Fukunaga, T., A. Matsuo, et al. (1978). Mechanical Power Output in Running. Baltimore, University Park Press.

Gage, J. R. (1991). Gait Analysis in Cerebral Palsy. (Clinics in Developmental Medicine (Mac Keith Press)) Cambridge University Press.

Goldberg, E. J., S. A. Kautz, et al. (2008). "Can treadmill walking be used to assess propulsion generation?" J Biomech **41**(8): 1805-1808.

Hanke, T. A. and M. W. Rogers (1992). "Reliability of ground reaction force measurements during dynamic transitions from bipedal to single-limb stance in healthy adults." Phys Ther **72**(11): 810-816.

Headon, R. and R. Curwen (2001). "Recognizing movements from the ground reaction force." Proceedings of the 2001 workshop on Perceptive user interfaces ACM - Digital Library

Kirtley, C. (2006). Clinical gait analysis : theory and practice. Edinburgh ; New York, Elsevier.

Kram, R., T. M. Griffin, et al. (1998). "Force treadmill for measuring vertical and horizontal ground reaction forces." J Appl Physiol **85**(2): 764-769.

Kuntze, G., W. I. Sellers, et al. (2009). "Bilateral ground reaction forces and joint moments for lateral sidestepping and crossover stepping tasks." Journal of Sports Science and Medicine **8**: 1-8.

Lake, M. and M. Robinson (2005). "Biomechanics of walking in different shoes: a comparison between overground and treadmill testing protocols." 7th Symposium on Footwear Biomechanics, Cleveland, Ohio USA, The International Society of Biomechanics Technical Group on Footwear Biomechanics.

Lee, S. J. and J. Hidler (2008). "Biomechanics of overground vs. treadmill walking in healthy individuals." J Appl Physiol **104**(3): 747-755.

Li, L. and J. Hamill (2002). "Characteristics of the vertical ground reaction force component prior to gait transition." Res Q Exerc Sport **73**(3): 229-237.

Masani, K., M. Kouzaki, et al. (2002). "Variability of ground reaction forces during treadmill walking." J Appl Physiol **92**(5): 1885-1890.

Murray, M. P., G. B. Spurr, et al. (1985). "Treadmill vs. floor walking: kinematics, electromyogram, and heart rate." J Appl Physiol **59**(1): 87-91.

Nigg, B. M. (1983). "External force measurements with sport shoes and playing surfaces." Proceedings of the International Symposium on Biomechanical Aspects of Sport Shoes and Playing Surfaces, Calgary, Canada, Biomechanics Laboratory, University of Calgary.

Nigg, B. M., R. W. De Boer, et al. (1995). "A kinematic comparison of overground and treadmill running." Med Sci Sports Exerc **27**(1): 98-105.

Nigg, B. M., J. Denoth, et al. (1981). Quantifying the Load on the Human Body: Problems and Some Possible Solutions. Baltimore, University Park Press.

Nilsson, J. and A. Thorstensson (1989). "Ground reaction forces at different speeds of human walking and running." Acta Physiol Scand **136**(2): 217-227.

O'Leary, K., K. A. Vorpahl, et al. (2008). "Effect of cushioned insoles on impact forces during running." J Am Podiatr Med Assoc **98**(1): 36-41.

Oggero, E., G. Pagnacco, et al. (1997). "Probability of valid gait data acquisition using currently available force plates." Biomed Sci Instrum **34**: 392-397.

Owings, T. M. and M. D. Grabiner (2004). "Step width variability, but not step length variability or step time variability, discriminates gait of healthy young and older adults during treadmill locomotion." J Biomech **37**(6): 935-938.

Payne, A. H. (1978). A Comparison of the Ground Forces in Race Walking with Those in Normal Walking and Running. Baltimore, University Park Press.

Perry, J. (1992). Gait Analysis : Normal and Pathological Function. Thorofare, NJ, SLACK.

Riley, P. O., J. Dicharry, et al. (2008). "A kinematics and kinetic comparison of overground and treadmill running." Med Sci Sports Exerc **40**(6): 1093-1100.

Riley, P. O., G. Paolini, et al. (2007). "A kinematic and kinetic comparison of overground and treadmill walking in healthy subjects." Gait Posture **26**(1): 17-24.

Rodano, R. and R. Squadrone (2000). "A procedure for quantitative kinematic analysis in running on treadmill." 18 International Symposium on Biomechanics in Sports, Hong Kong, China.

Savelberg, H. H., M. A. Vorstenbosch, et al. (1998). "Intra-stride belt-speed variation affects treadmill locomotion." Gait Posture **7**(1): 26-34.

Scott, S. H. and D. A. Winter (1990). "Internal forces of chronic running injury sites." Med Sci Sports Exerc **22**(3): 357-369.

Sohn, R. H., S. H. Hwang, et al. (2009). "Comparison of motion analysis and energy expenditures between treadmill and overground walking." 13th International Conference on Biomedical Engineering. C. T. Lim and J. C. H. Goh, Springer Berlin Heidelberg. **23:** 1928-1930.

Stolze, H., J. P. Kuhtz-Buschbeck, et al. (1997). "Gait analysis during treadmill and overground locomotion in children and adults." Electroencephalogr Clin Neurophysiol **105**(6): 490-497.

Toussaint, H. M., D. A. Commissaris, et al. (1995). "Controlling the ground reaction force during lifting." J Mot Behav **27**(3): 225-234.

van Ingen Schenau, G. J. (1980). "Some fundamental aspects of the biomechanics of overground versus treadmill locomotion." Med Sci Sports Exerc **12**(4): 257-261.

Veltink, P. H., C. Liedtke, et al. (2005). "Ambulatory measurement of ground reaction forces." IEEE Trans Neural Syst Rehabil Eng **13**(3): 423-427.

Watkins, J. (2007). An introduction to biomechanics of sport and exercise. New York, Churchill Livingstone.

White, S. C., H. J. Yack, et al. (1998). "Comparison of vertical ground reaction forces during overground and treadmill walking." Med Sci Sports Exerc **30**(10): 1537-1542.

Winter, D. A. (1983). "Moments of force and mechanical power in jogging." J Biomech **16**(1): 91-97.

Winter, D. A. (1984). "Kinematic and kinetic patterns in human gait: Variability and compensating effects." Hum Mov Sci **3**(1–2): 51-76.

www.motion-labs.com. from Motion Lab Systems: http://www.motion-labs.com.

Zeni, J. A., Jr. and J. S. Higginson (2010). "Gait parameters and stride-to-stride variability during familiarization to walking on a split-belt treadmill." Clin Biomech (Bristol, Avon) **25**(4): 383-386.