Montview Liberty University
Journal of Undergraduate Research

Volume 3 | Issue 1 Article 3

2017

The Effect of Barefoot Running Using Two Running Styles on Lower Extremity Joint Reaction Forces

Jamie M. Rogers EP-C
Liberty University, jrogers109@liberty.edu

Recommended Citation

Rogers, Jamie M. EP-C (2017) "The Effect of Barefoot Running Using Two Running Styles on Lower Extremity Joint Reaction Forces," *Montview Liberty University Journal of Undergraduate Research*: Vol. 3 : Iss. 1 , Article 3.
Available at: http://digitalcommons.liberty.edu/montview/vol3/iss1/3

The Effect of Barefoot Running Using Two Running Styles on Lower Extremity Joint Reaction Forces

Jamie M. Rogers

A Senior Thesis submitted in partial fulfillment
of the requirements for graduation
in the Honors Program
Liberty University
Spring 2017

Acceptance of Senior Honors Thesis

This Senior Honors Thesis is accepted in partial fulfillment of the requirements for graduation from the Honors Program of Liberty University.

____
David Titcomb, PT, DPT, EP-C
Thesis Chair

____
Jeffrey Lowes, D.C., EP-C
Committee Member

____
David Dinsmore, Ed.D., P.E.
Committee Member

____
Marilyn Gadomski, Ph.D.
Honors Assistant Director

____
Date

Abstract

Running is a popular worldwide activity with many varying biomechanical techniques. Investigating potential differences in joint forces can be beneficial in determining if there is a superior biomechanical running pattern. Previous research compared barefoot and shod running, as well as the kinetic effects of varied running styles. The current study investigated the differences in internal joint reaction forces (JRF) at the hip, knee, and ankle joints during running with two different styles. Ten male and ten female participants who naturally run with a rearfoot strike pattern were included in this study. Each subject ran barefoot on an instrumented treadmill for two trials with a natural rearfoot strike and two trials with an induced forefoot strike. Peak JRF data were averaged from five strides during both conditions to determine the peak forces experienced at the ankle, knee, and hip in the X, Y, and Z planes. Statistical analyses of the results via paired samples t-tests revealed no statistical difference between rearfoot and forefoot running patterns. The results of this study suggest that there may be no superior foot strike pattern to reduce JRFs in the lower extremity. The conclusions from the current study supported findings from prior research. Additional research is recommended to gain more insight as to whether or not a superior running pattern does exist. If this is the case, runners could improve their biomechanical efficiency and potentially reduce the incidence of overuse injuries.

The Effect of Barefoot Running Using Two Running Styles on Lower Extremity Joint Reaction Forces

The Running Gait Cycle

There are two phases of the running gait cycle: stance and swing. The stance phase begins at the first instance in which the foot contacts the ground. This specific point is known as the initial contact. One full gait cycle begins at the initial contact (also referred to as strike pattern) of one leg and ends at the initial contact of the same leg during the next stride (Schneck & Bronzino, 2003). The initial contact is extremely important to analyze in a runner as it is the point where the body quickly absorbs the ground impact (Houglum & Bertoti, 2012). The end of the stance phase is known as the toe off. The swing phase includes the entire time the observed leg is in the air from toe-off to the next initial contact. During running, the swing phase is nearly two-thirds longer than the stance phase (Schneck & Bronzino, 2003).

Feet and the Influence on Running Biomechanics

The foot is the body part which contacts the ground; therefore, it may be the most influential part in determining effects of forces during running. The ankle joint is the first joint to experience the forces that travel up the body. Specifically, the amount of pronation can play an important role in forces experienced by runners (Bishop, Fiolkowski, Conrad, Brunt, & Horodyski, 2006). Pronation is a movement of the foot “defined as a combined movement of calcaneal eversion, forefoot abduction, and dorsiflexion” (Rabiei, Eslami & Movaghar, 2016, p.11). Pronation is a normal occurrence during the stance phase of gait and causes shock absorption to occur after initial impact on the heel by unlocking the foot. However, there can be biomechanical issues observed if too much or too little pronation occurs in a runner (Rabiei et al., 2016). Research has observed an increase in lower extremity stiffness for subjects with high arches and a decrease in lower extremity stiffness for low arched subjects. High arched runners tend to experience more bony injuries while the opposite biomechanical effect occurs for low arched runners, causing injuries that occur in mainly in soft tissues (Bishop et al., 2006; Williams, McClay, & Hamill, 2001). Runners with a low arch tend to have increased pronation and high arched runners tend to have a decreased amount of pronation (also called supination) (Golightly, Hannan, Dufour, Hillstrom, & Jordan, 2014). Thick soled running shoes have demonstrated an increase in the pronation-causing effects at the ankle (Daoud et al., 2012).

Importance of Foot Strike Patterning in Running

There are three significant types of initial contact or foot-strike patterns: rearfoot, midfoot, and forefoot. Rearfoot runners have initial contact with the heel on the ground. Midfoot runners land with the heel and ball of the foot at the same time. Forefoot strikers initially land on the ball of the foot before the heel makes ground contact. Running is frequently used as a means of physical activity and exercise for many people throughout the world. However, due to the mixture of repetitive kinematic and kinetic forces involved over long distances, runners frequently experience lower-extremity injuries (Almeida, Davis, & Lopes, 2015). Some studies report up to eighty percent of runners will experience a lower-extremity injury (van Gent et al., 2007). These injuries are often due to how an individual’s body controls and absorbs shock from the impact of the foot repetitively hitting the ground over time (Cavanagh & Lafortune, 1980).

Biomechanically, the lower extremity acts similar to a spring absorbing shock from the ground impact and then recoiling to assist in pushing the body off the ground to move forward (Bishop et al., 2006). Vertical forces, such as the Ground Reaction Force (GRF), and horizontal forces (mediolateral or anterior-posterior forces) are all involved in running (Cavanagh & Lafortune, 1980). The GRF is the equal and opposite impact the body experiences during its impact with the ground due to Newton’s Third Law of Motion (Houglum & Bertoti, 2012). The GRF in a recreational runner commonly reaches up to two and a half times body weight. However, the joint contact forces themselves can reach higher magnitudes up to 15 times body weight. Therefore, the JRFs may be more important to study because the GRF may be underestimating the forces experienced by body tissues during running. The internal joint loading may be a more direct measurement of what the joint is experiencing. (Rooney & Derrick, 2013). The internal joint forces are those that the muscles, tendons, and ligaments of the body must experience and absorb with each contact the foot makes with the ground (Houglum & Bertoti, 2012). Specific running styles, variability in footwear, and foot-to-ground contact are thought to help the body cope with the repetitive forces a runner must endure (Paquette, Milner, & Melcher, 2016).

Studies in current literature are trying to reveal a unique biomechanical difference in how each foot-strike pattern deals with forces traveling up the lower extremity chain (Almeida et al., 2015). Many studies only observe aspects between rearfoot and forefoot strike patterns (Rooney & Derrick, 2013; Stearne, Alderson, Green, Donnelly, & Rubenson, 2014; Yong, Silder, & Delp, 2014). Injury rates are greater in habitual rearfoot strikers than habitual midfoot or forefoot strikers. Common injury sites include the lumbar spine, femoroacetabular region, tibiofemoral region, tibia, and plantar fascia

(Kuhman, Melcher, & Paquette, 2015). Studying the biomechanical differences between foot strike patterns utilized by runners will show variations in forces, power, work, and range of motion (ROM) from each pattern. This can lead to determining the possible differences in risk, occurrence, and locations of injuries (Stearne et al., 2014).

Footwear and the Influence on Running Biomechanics

Previously, it was assumed that the best running style should emphasize a rearfoot strike pattern, thus leading to the development of the modern running shoe in the 1970s. Shoe companies designed what is now known as the traditional running shoe with a heel cushion that provides a minute lift that contributes to the rearfoot strike pattern with the heel hitting the ground first (Lieberman et al., 2010). However, recently, this philosophy is changing within the running community. Due to the research observing increases in GRF during a rearfoot initial contact pattern, questions have arisen regarding the value of a forefoot strike pattern with minimalist footwear. Minimalist shoes discourage a rearfoot contact pattern due to decreased or no heel cushion compared to the traditional running shoe. These shoes do not have the lift observed in the soles, therefore encouraging a more equalized heel-to-toe drop (Rice, Jamison, & Davis, 2016).

The rise of minimalist (lack of cushion) running ideology within the new millineum is changing the previous thoughts about running. The current interest in barefoot/minimalist running is due to the popular speculation and media presumption that this form of running is more efficient and may decrease overuse injury potential in runners due to the natural transition to a forefoot impact (Thompson, Seegmiller, & McGowan, 2015). When running barefoot, the body’s natural foot strike pattern is landing on the forefoot to avoid the harsh heel impact with the ground (Lieberman et al., 2010). Wearing shoes (shod) and barefoot conditions are observed to have alternate kinetic and kinematic effects. However, no statistical differences were noted between types of shoes and amount of cushioning on the kinetic and kinematic effects (Bishop et al., 2006). Strangely, other researchers believe that a foot strike pattern may still be independent of footwear due to studies on habitually barefoot populations (Almonroeder, Willson, & Kernozek, 2013). Increased vertical GRFs are observed with a barefoot rearfoot strike pattern as compared to a barefoot forefoot strike pattern (Almeida et al., 2015). On the other hand, barefoot forefoot running has shown a fifteen percent increase in the loading rate of the Achilles tendon when compared to a barefoot rearfoot strike pattern (Almonroeder et al.). According to Yong et al. (2014), the popularity of forefoot strike patterning (in addition to minimalist running) is increasing to hopefully decrease injury risks by utilizing the original biomechanical pattern for which our body appears to naturally desire.

Speed and the Influence on Running Biomechanics

Previous research has concluded the direct relationship between speed and a forefoot strike pattern. Increases in velocity correlate with a more anterior initial foot strike (Breine, Malcolm, Frederick, & De Clercq, 2014). Moreover, increases in running velocity have been correlated with a direct increase in leg stiffness. This increased stiffness is believed to be a factor in predicting possible injury (Butler, Crowell, & Davis, 2003). Specifically, barefoot runners demonstrate increased joint excursion with a corresponding increase in speed during the stance phase (Bishop et al., 2006).

Rearfoot Strike Pattern

Between seventy and ninety percent of runners utilize a rearfoot strike pattern (Almeida et al., 2015; Thompson et al., 2015). Some researchers believe that this style of initial contact is attributed to the modern running shoe with its increased heel lift of cushion. This extra lift causes a runner to land on his/her heel due to the closer proximity of the heel to the ground (Almeida et al., 2015; Lieberman et al., 2010). A rearfoot heel strike may also result in a unique sequence of events during the rest of the gait cycle. For example, biomechanically, this can initiate the following running form during the initial stance phase: the foot lands ahead of the body, allowing the knee to extend and the ankle to dorsiflex, invert, and abduct. To propel the runner, the calf must then contract with enough force to allow the runner to move over the foot and go into swing phase (Daoud et al., 2012). When compared to other running patterns, the rearfoot strike pattern demonstrates an increase in ground contact time and a slower running velocity (Valenzuela, Lynn, Mikelson, Noffal, & Judelson, 2015). A rearfoot strike pattern also causes increased vertical loading rates during running (Almeida et al., 2015; Goss et al., 2015; Kuhman et al., 2015) as well as overall vertical impact forces (Bishop et al., 2006; Kulmala, Avele, Pasanen, & Parkkari, 2013; Yong et al, 2014).

Another interesting feature that occurs during a rearfoot strike is the presence of two peaks of vertical force data during an initial foot strike (Cavanagh & Lafortune, 1980). The initial spike is commonly known as an impact transient. It occurs during the first fifty milliseconds of the heel strike and is followed by the main vertical force, the GRF (Valenzuela et al., 2015). That impact transient is generated by the initial high-force impact from the heel onto the ground with minimal energy absorption. This results in the transfer of the GRF directly up the lower extremity chain (Almeida et al., 2015). As noted above, the impact transient is almost exclusively seen in rearfoot runners and is thought to contribute to the increased injuries seen with runners who utilize this foot-strike pattern (Valenzuela et al., 2015). Due to these increased forces, rearfoot runners usually run shod to gain an extra cushion effect from the shoe (Almeida et al., 2015). If they transition to minimalist shoes, these runners tend to develop a forefoot strike pattern to decrease the large GRF initiated on the calcaneus (Boyer, Rooney, & Derrick, 2014).

Forefoot Strike Pattern

A forefoot strike pattern has been associated with increased velocity in runners compared to their rearfoot counterparts (Bishop et al., 2006; Stearne et al., 2014). Also, forefoot strikers tend to run with a shorter stride length (Bishop et al., 2006), decreased duration in stance phase, and an increased stride frequency. The forefoot (and midfoot) strike pattern is more utilized in elite, rather than recreational, runners. A runner utilizing a forefoot strike pattern will experience more stress at the ankle joint in the sagittal plane (Stearne et al., 2014).

Comparisons of the Joint Effects between Rearfoot and Forefoot Initial Contact Patterns

The ankle joint displays the greatest differences observed between the two strike patterns. The ankle joint demonstrates increased dorsiflexion during initial foot strike in the rearfoot strike pattern. This coincides with increased tibialis anterior stimulation, peak dorsiflexion moments, and increased ankle joint moments during the initial strike (Kuhman et al., 2015; Paquette et al., 2016; Yong et al., 2014). On the other hand, the forefoot strike pattern is associated with increased loading at the ankle joint (Kuhman, et al., 2015). Landing on the ball of the foot allows for increased ankle plantarflexion at foot impact, allowing for increases in gastrocnemius and soleus activation (Yong et al., 2014), specifically increased eccentric plantarflexion power (Kuhman et al., 2015; Stearne et al., 2014). This has been shown to increase stresses on the Achilles tendon (Kulmala et al., 2013; Rooney & Derrick, 2013), and lead to increased instability to forefoot runners (Fredericks et al., 2015). During a rearfoot strike pattern, the ankle is stiffer than the knee; conversely, a forefoot pattern exhibits the reverse relationship with knee stiffness greater than at the ankle (Butler et al., 2003).

Research has also observed differences at the knee joint. Utilizing a rearfoot strike pattern may stress the knee joint most in the sagittal and frontal planes (Stearne et al., 2014). In a meta-analysis of the literature, increased knee flexion ROM was observed for natural shod rearfoot strikers (Almeida et al., 2015), except at initial contact (Yong et al., 2014). This seems to be due to the decreased stride length in a forefoot runner (Almeida et al., 2015). Overall, the forefoot strike pattern coincides with decreased knee loading and patellofemoral stresses when compared to a rearfoot strike (Kulmala et al., 2013).

Common Injuries Linked to Strike Pattern

A frequently studied aspect of running has been the analysis of the individual foot-strike pattern, and its possible contribution to kinematics, kinetics, and lower-extremity injury rates. The foot is the contact between the runner and the ground; therefore, it may be the most essential aspect in analyzing the link between the forces that travel up the lower extremity chain in a runner and subsequent injury rates (Rooney & Derrick, 2013). Common injuries for runners include back pain, hip pain, patellofemoral pain, plantar fasciitis, medial tibial stress syndrome, Achilles tendinopathies, and iliotibial issues (Cheung & Davis, 2016; Daoud et al., 2012; Kuhman, Melcher, & Paquette, 2015; Stearne et al., 2014). Joint stiffness has been thought to play a major role in injury rate (Butler et al., 2003). Half of the injuries runners experience surround the tibiofemoral joint (Goss et al., 2015). Furthermore, the majority of injuries affect the lower extremity tendons (Mann et al., 2015). Rearfoot strike patterns have been observed to double the rates and slightly increase the severity of overuse injuries when compared to forefoot runners in some studies, but other studies have not been able to demonstrate a correlation. However, other factors do play a major role in injures as well, including gender, running distance, arch type, core strength, bone structure, and mileage per week (Daoud et al., 2012; Milner, Ferber, Pollard, Hamill, & Davis, 2006). The impact transient observed during rearfoot running has been thought to be associated with increases in tibial injuries and plantar fasciitis (Almonroeder et al., 2013). Furthermore, a rearfoot strike pattern has been associated with increased injury rates at the knee and hip (Daoud et al., 2012).

Rearfoot strike patterns have been linked to increases in patellofemoral pain. This has been suggested to be influenced by the increased knee extension moments. Some researchers have suggested landing training for runners to reduce chances of this injury. Symptoms have been shown to decrease with landing training and shifting away from a rearfoot strike pattern (Cheung & Davis, 2016). Greater stride lengths have been observed to increase patellofemoral stresses. Due to the significant increases in patellofemoral stress during rearfoot running, some researchers believe this may indicate a reason to modify strike pattern away from the traditional rearfoot strike to shorten stride length and to aid in decreasing injury rates (Vannatta & Kernozek, 2015; Willson, Ratcliff, Meardon, & Willy, 2015).

Previous incidence of medial tibial stress syndrome in female runners has been shown to increase running-related loading variables. Higher impact peaks and knee joint stiffness were observed with these subjects. As these loading variables relate heavily toward tibial stress, it can be assumed that reoccurrence is likely for tibial stress issues (Milner et al., 2006).

The forefoot strike pattern has been thought to lead to increased instability that can pose injury risks to forefoot runners (Fredericks et al., 2015). Due to the increase in ankle moments for a forefoot striker (Daoud et al., 2012), it is assumed that an increase in ankle injuries and Achilles tendinopathies may increase with this running pattern (Almonroeder et al., 2013; Mann et al., 2015). Even though the Achilles tendon is known for its ability for eccentric control, overstressing the tendon through the increased negative power from the forefoot strike can lead to overuse injuries (Stearne et al., 2014). Greater impulses and loading rates are observed in the Achilles tendon while utilizing a forefoot strike pattern. Therefore, the forefoot pattern is thought to lead to an increase in Achilles injuries for those with a previous history of Achilles issues. However, it is assumed that utilizing a forefoot strike can decrease occurrences of other injuries, such as tibial stress fractures, plantar fasciitis, and patellofemoral issues (Almonroeder et al., 2013).

Research Conclusions on a Superior Foot Strike Pattern

Conclusions on a recommended strike pattern are difficult to determine because the research shows no clear conclusions and many variable results (Valenzuela et al., 2015). Some researchers believe it may be beneficial in the reduction of injury to change from a rearfoot running pattern to a forefoot strike pattern (Stearne et al., 2014). One study on rearfoot strikers observed that the compression of the tibia occurred by muscular forces, but tibial shear was caused by internal joint reaction forces. Therefore, some researchers believe forefoot running may decrease stress fracture injuries of the tibia (Sasimontonkul, Bay, & Pavol, 2007).

If a runner decides to alter his/her foot strike pattern, it is suggested to maintain a smooth and gradual transition to aid in decreasing injury rates to the body tissues adapting to new physical stresses (Kuhman et al., 2015). Altering a foot strike pattern can cause injuries due to the shift of different kinematic and kinetic motion and forces on lower extremity (Stearne et al., 2014). When a habitual rearfoot striker acutely alters his/her running mechanics toward a forefoot strike pattern, the following effects are initially seen: little or no impact transient, reduced loading rate, decreased step length, increased plantarflexion motion and power, increased eccentric plantarflexion power, and decreased knee extensor forces and power (Kuhman et al., 2015).

However, other researchers are not completely convinced the forefoot strike is a superior running pattern. They believe that runners are trying to alter their footstrike pattern based on “unsubstantiated claims” that forefoot and midfoot running can decrease injuries or improve performance (Daoud et al., 2012, p. 1326). Since forefoot running requires increased ankle ROM, some researchers assume that it may increase injuries in runners lacking the necessary motion. Decreased ankle ROM can cause a reduction in shock absorption, increased external forces, and decreased knee and hip flexion while in a forefoot running pattern (Bishop et al., 2006). Furthermore, a meta-analysis of research involving foot strike patterning observed no significant difference between natural shod rearfoot and midfoot strike patterns, specifically when looking at the second peak of vertical GRF data and stride length. Similarly, there were no determined differences between natural shod rearfoot and forefoot strikers when observing the second peak of vertical GRF, cadence, total lower extremity power, total lower extremity work, and the ankle plantar flexion moment (Almeida et al., 2015; Stearne et al., 2014). However, rearfoot runners did have a significant increase in vertical loading rates (Almeida et al., 2015).

Short-term studies on imposed forefoot strike patterns in rearfoot runners observe similar mechanics in the sagittal plane for habitual forefoot strikers. However, the transverse plane mechanics at the ankle showed a one-third increase in internal rotation, and an increase of almost fifty percent in frontal plane abduction at the knee joint. Lower extremity work and power were also increased with the forefoot strike imposition. This might be a disadvantage to a runner due to the increased stress placed on the musculoskeletal system to accommodate the increased workload. Furthermore, oxygen consumption has been observed to increase with the imposed forefoot strike pattern, probably due to the increased workload resulting from new demands on the runner’s body. As expected, these runners also displayed plantarflexor soreness and fatigue due to the increase in eccentric calf contraction (Stearne et al., 2014).

Also, there are some researchers who do not believe changing to a forefoot strike pattern will help in decreasing risk for injury due to similar GRF data in rearfoot strikers (Boyer et al., 2014), especially during acute or quick transitioning of strike patterns (Kuhman et al., 2015; Stearne et al., 2014). One group of researchers proposed the opposite effect to reduce and rehabilitate ankle injuries: switching from a forefoot strike pattern to a rearfoot strike (Stearne et al., 2014). Furthermore, one study determined that a similar injury occurrence exists between rearfoot and forefoot runners with variation only in injury location and causation (Stearne et al., 2014). These conclusions are only based on shod runners as there is not enough kinematic research for barefoot runners to make any deductions with that condition.

Therefore, the current research shows no conclusion on which foot strike pattern is best for a runner to utilize (Almeida et al., 2015; Stearne et al., 2014). Total work and power observed in the lower extremity is similar from both rearfoot and forefoot strikers, indicating no mechanical advantage of a single foot strike pattern. However, work and power seem to be distributed differently among musculoskeletal structures, causing possible injury risk differences among the different strike patterns. Since the rearfoot strike causes more stress at the knee during stance phase, the majority of runners are rearfoot strikers, and the majority of injuries are located at the knee, it can be assumed that runners who utilize the rearfoot strike pattern contribute more to the injury prevalence. However, the forefoot strike pattern places more stress at the ankle, so it may be assumed that the forefoot strike pattern could contribute to an increase in injury prevalence at the ankle due to the increased mechanical liability at this joint (Stearne et al., 2014).

Another conclusion substantiated by other research is that variability in running can decrease injury risks. If the lower-extremity tissues experience the same distribution pattern of forces, they are at an increased risk of injury (Kuhman et al., 2015). If runners can alter their running shoes, terrain, stride, foot strike, and foot contact angle throughout their recreational or competitive running, it may decrease injury rates over time due to decreasing similar stresses on body tissues (Paquette et al., 2016). Therefore, there may be little to no difference in injury prevention by campaigning for a specific strike pattern. Presumably, similar injury risks can be due to overuse of body tissues through repetitive activity with no variability, leading to disrepair (Kuhman et al., 2015).

Due to the lack of research and conclusions on a definitive type of strike pattern, it seems the answer may lie either with individual preference based on personal deficiencies, previous injury, sex, footwear, available ROM, body composition, training schedules, (Daoud et al., 2012) level of runner (Stearne et al., 2014), or with introducing variability within the running routine (Paquette et al., 2016). There does not seem to be a definite biomechanical supremacy of one foot strike pattern to another (Stearne et al., 2014) due to the many variations of biomechanical differences in runners (Daoud et al., 2012).

Future Research

It is recommended that future researchers continue to investigate kinetic and kinematic variables during running to expand the knowledge of this issue. There are insufficient quantities of research studies in this area to make definite conclusions about the best running strike pattern (Almeida et al., 2015). A rearfoot strike pattern has been shown to increase the vertical GRF at initial contact, and so it may be reasonable to assume that this strike pattern can lead to increases in running-related injuries. On the other hand, the forefoot strike pattern will increase gastrocnemius and soleus eccentric activation, leading to possible increases in Achilles running-related injuries. Both of these running effects can contribute to injury, making it difficult to ascertain the best foot strike pattern for a runner (Almeida et al., 2015; Almonroeder et al., 2013).

There are many follow-up questions that need to be answered by future research. Are there significant differences in kinetic data in the lower extremity chain between strike patterns? Can these differences conclusively be linked to possible increase in injury? Are there any conclusions to suggest whether or not internal joint forces relate better to injury predictions than GRFs? Is there a foot strike pattern that demonstrates increased internal joint forces? In which plane of motion are the lower extremity joints under most internal force during rearfoot and forefoot strike patterns? The following study attempts to begin the journey to answer these questions. In this study, it is assumed that internal joint forces will more accurately demonstrate the forces the body experiences than GRFs (Rooney & Derrick, 2013).

Experimental Introduction

The purpose of the current study was to observe and compare JRFs between rearfoot and forefoot strike patterns to determine if any consistency exists in the force loading patterns within each running style, with the hope of determining if a connection can be made between forces observed and initial contact pattern. The hypothesis for this study is that there will be a significant difference between the JRFs observed between the rearfoot and forefoot strike patterns. Each major lower extremity joint (hip, knee, and ankle) was observed for each plane of motion to determine if any significant kinetic effect between the two running styles was noted up the lower extremity chain.

Method

Subjects

Twenty runners were recruited for this study: ten males and ten females. Based on verbal questioning, each participant met the following criteria: currently a recreational runner as defined by running bouts of 3-10 miles habitually at least 2 days per week, between 18 and 50 years of age, run with a heel strike, and free from any injury that could affect running performance. This study was approved by the Liberty University International Review Board before any experimentation was conducted.

Prior to testing, each participant read and signed an informed consent. Additionally, all subjects completed an American College of Sports Medicine (ACSM) risk stratification form. Only those who were revealed to be low risk per ACSM standards were allowed to participate in the study. Any participants who were moderate or high risk were exempt from the study to decrease risk of an injury or a health issue during testing procedures.

Materials

The following equipment was used in the current study:

- Vicon Nexus software (Oxford, UK)
- AMTI (Watertown, MA) instrumented treadmill
- Two Bonita high speed cameras (Oxford, UK)
- Ten three-dimensional optical motion analysis Vicon cameras (Oxford, UK)
- Vicon Polygon software (Oxford, UK)
- IBM SPSS software (Armonk, NY)

Procedures

The participants performed four trials each: two with a natural rearfoot strike and two with an imposed forefoot strike. After the individual rearfoot pattern trials, subjects were instructed on how to run with a forefoot strike pattern and then were allowed to practice the technique (with verbal cuing from the researcher) until they felt comfortable with the imposed strike pattern. Once the subjects were prepared for the test run, they performed the last two test trials with the imposed forefoot strike pattern. Five complete strides were recorded after each subject was accustomed to running on the treadmill. If data for the trial was incomplete or incorrect, a third trial was conducted to ensure optimal and accurate data. Once the examiner determined that each subject did not exhibit any ill effects from the procedure, the subject was allowed to leave the testing area.

Subjects were instructed to remain barefoot throughout the testing procedures to minimize any effects from various footwear, as similar footwear for each subject could not be reasonably attained. Males were instructed to wear compression shorts and females were to wear spandex shorts and a sports bra to allow for optimal data collection through motion capture and video recording. Height, weight, leg length, ankle width, and knee width were measured, recorded, and entered in the Vicon Nexus software utilized for data collection. Lower extremity joint markers were adhered to the body using double-sided tape for motion capture reading ability. Markers were placed at left and right posterior superior iliac spine (PSIS), anterior superior iliac spine (ASIS), lateral thigh, lateral tibiofemoral joint, lateral tibia, posterior calcaneus, and the dorsum of second metatarsal head. Each subject was instructed on how the treadmill force plates work and the correct foot placement technique needed for similar data collection between participants. Proper instruction of getting on and off the treadmill was coached prior to running for safety purposes. Kinetic data were collected from an instrumented AMTI instrumented treadmill. Force data sampling rate was set at 1000 Hz and then downsampled to 100 Hz during data processing. Kinetic data capture was synchronized with kinematic video and optical motion capture. Video capture from two Bonita high speed cameras (sampling rate set at 100 Hz) and ten three-dimensional optical motion analysis Vicon cameras (sampling rate set at 200 Hz) were utilized. Three-dimensional motion analysis data capture was performed using Vicon Nexus software. Running velocity of each subject was standardized at five miles per hour.

Three-dimensional joint reaction forces of each subject's left and right hip, knee, and ankle joints during the trials were graphed using Vicon Polygon software. For analysis of each subject, one recorded trial was selected for rearfoot analysis and one recorded trial was selected for the forefoot analysis based on which trial had the most complete data without gaps. Five highest peaks were recorded for the right and left hip, knee, and ankle joints based on the direction of the highest forces observed in the JRF X, Y, and Z axis graphs. These peaks were averaged by the investigator using Microsoft Excel to determine the average peak joint reaction force during five running strides. Data were then exported into SPSS statistical software to compare intrasubject data between the rearfoot and forefoot strike pattern. A paired samples t-test was utilized for data analysis to compare running styles for each subject. Statistical significance was set at $p<.05$.

Results

Table 1 summarizes the participant demographics. This study utilized ten males and ten females as subjects. The average male height, mass, and age was 177.46 cm, 77.94 kg, and 34.1 years, respectively. Average female height, mass, and age was 165.00 cm, 57.85 kg, and 25.00 years, respectively.

Table 2 displays the results of the paired samples t-test for each variable analyzed when comparing all subjects together. No p value was less than the accepted value of .05, indicating no significant difference in any JRF observed in any of the investigated joint planes. An additional t-test analysis was also conducted in order to compare gender-specific results which are displayed in Table 2. No statistically significant correlation was found for either analysis.

Table 3 displays minimum, maximum, range, mean, and standard deviation for each internal joint force analyzed for all 20 subjects. The largest observed average force values were noted for both the rearfoot and forefoot conditions at the ankle joint in the X plane. The values of 19.231 [standard deviation (SD) 3.166] N·BW and 18.969 (SD 3.557) N·BW for the rearfoot conditions were slightly higher than corresponding forces observed in the forefoot condition: 18.930 (SD 4.912) N·BW and 18.727 (SD 5.475) N·BW. The smallest average forces of 0.805 (SD 2.663) N·BW and 0.746 (SD 2.562) N·BW were observed in both conditions at the hip joint in the Y plane, again with the rearfoot average the greatest of the two.

Tables 4 and 5 also display minimum, maximum, range, mean, and standard deviation of the measured forces, though observing each gender group separately. It was observed that males and females each experienced the greatest average force values in the X plane of the ankle joint. For males, the values of 18.793 (SD 3.325) N·BW and 19.969 (SD 3.3.258) N·BW for the rearfoot conditions were slightly lower than corresponding forces observed in the forefoot condition: 20.093 (SD 2.868) N·BW and 20.338 (SD 2.856) N·BW. For females, the values of 19.668 (SD 3.303) N·BW and 18.857 (SD 4.107) N·BW for the rearfoot conditions were slightly higher than corresponding forces observed in the forefoot condition: 17.980 (SD 6.416) N·BW and 17.515 (SD 7.154) N·BW. Males experienced the lowest average force at the ankle joint in the Y plane in the rearfoot condition: 0.769 (SD 2.649) N·BW. Females, however, experience their lowest average forces of 0.742 (SD 2.620) N·BW and 0.672 (SD 2.458) N·BW in the hip joint in the Y plane for the rearfoot and forefoot conditions, respectively.

Figures 1-9 graphically depict the average maximum force observed during five steps in each joint and plane of motion during both treadmill runs for each subject.

Discussion

This research investigated the acute effects of an induced forefoot strike pattern as compared to a natural rearfoot strike pattern by analyzing the internal JRFs of the hip, knee, and ankle joints. A recent trend in running is to transition from a natural rearfoot strike pattern toward a midfoot or forefoot strike in order to increase running performance or decrease potential injury (Fredericks et al., 2015; Kuhman et al., 2015; Stearne et al., 2014). However, no studies have consistently shown a significant decrease in running injuries based on this change (Valenzuela et al., 2015). There is a lack of recent research that investigates the effects of foot strike pattern on JRFs. Most research has focused mainly on the GRFs observed in runners with respect to strike pattern

(Cavanagh & Lafortune, 1980; Daoud et al., 2011; Kuhman et al., 2015; Kulmala et al., 2013; Rooney & Derrick, 2013). However, direct observation into what the joints are experiencing may provide insight into prevention of running injuries (Rooney & Derrick, 2013).

Could the increase in the popularity of the forefoot strike pattern among recreational runners be due to the adoption of the foot strike utilized by elite runners (Stearne et al., 2014)? Recreational runners demonstrate lower mileage, velocities, and frequency of training compared to the elite runners (Daoud et al., 2012). Therefore, adoptions in running biomechanics from the elite group may be contraindicated.

Since different running speeds have been thought to cause variable forces in runners due to altering the joint kinematics, and possibly influencing the strike pattern (Fredricks et al., 2015), the speed was kept constant for all participants in this study. The barefoot condition was chosen for the current study because footwear could not be kept constant among participants and other research has found that inconsistent footwear does influence strike pattern (Fredricks et al., 2015). Furthermore, research has shown that similar loading rates occur with standard running shoes for different footstrike patterns (Rice et al., 2016). This study focused on the barefoot condition in order to investigate the kinetic effects involved between the two strike patterns while negating any standardized effects from variable running shoes.

The results of the current study performed at Liberty University suggest there are no significant changes in JRFs during an acute transition to a forefoot strike pattern. Moreover, this research suggests there is no implication of a superior strike pattern, which is in agreement with other researchers’ findings (Stearne et al., 2014). The results of the current study imply that foot strike patterns do not produce consistent force production at the lower extremity joints, therefore demonstrating that foot strike pattern produces variable force effects among individuals. As the foot is the body part to contact the ground, it takes the brunt of the impact forces. Therefore, the initial contact pattern has most of its effects at the ankle joint (Rooney & Derrick, 2013). The current study suggests that even at the ankle joint there were no significant differences between the opposing foot strike patterns.

It has been found in the literature that GRF increases with barefoot rearfoot strike patterning as compared to barefoot forefoot running (Almeida et al., 2015). However, the results of this study demonstrate no significant difference when directly observing JRFs during barefoot rearfoot and forefoot running, therefore suggesting GRF does not directly link to internal joint forces. One study also revealed that habitually shod rearfoot strikers tend to run similar to midfoot/forefoot strikers when in the barefoot condition. Therefore, based on these findings, participants in the current study were instructed to land on the heel during their barefoot rearfoot trials to maintain a true rearfoot strike pattern to compare to the forefoot pattern (Thompson et al., 2015).

The results of the current study support other research findings which suggest variability in runners contribute toward differing biomechanical stresses (Daoud et al., 2012; Stearne et al., 2014). As the current study focused on JRFs during opposing strike patterns, the findings suggest that a certain foot strike does not directly cause increased forces observed during running, but that many other factors are involved that load the body repeatedly: muscular weakness, gender, age, running age, pronation, mobility, running surface, footwear, or other controllable and uncontrollable factors (Phinyomark, Hettinga, Osis, & Ferber, 2014). Other research does denote repetitive movements as a strong contributor toward running injuries (Valenzuela et al., 2015) as well as the influence of fatigue over the course of a run (Benson & O'Connor, 2015). The assumption of a variety of factors contributing to injury risk does coincide with a concurrent review of the literature studying strike patterns, as there are no clear conclusions of a superior strike pattern as a way to decrease the potential for injury.

Results of the current study were compared to those found by Rooney and Derrick (2013) as this study is one of few that also observed internal joint forces. However, their research observed internal joint contact loading instead of joint reaction forces. Joint loading includes both the joint reactions forces as well as the forces experienced from the muscles. Both studies did not find any significant difference between running styles at the knee or hip joints. However, Rooney and Derrick did observe greater ankle contact force for the forefoot strike pattern. This current study supports the conclusions of Rooney and Derrick: "there is no evidence to support a difference between habitual and converted running for joint contact forces" (Rooney & Derrick, 2013, p. 2201).

The current research study does include limitations which should be addressed. Although footwear was eliminated from this study for the purpose of decreasing effects from inconsistent type of footwear, we know most runners do not run barefoot. Therefore, there may have been biomechanical changes that could have influenced the results or make them inapplicable to the shod running population. Moreover, even though each participant was extensively verbally questioned to confirm that they were a rearfoot strike runner, there was no measured or video-based confirmation. Also, the participants in this study were normalized to run at the same speed of five miles per hour. Due to differences in preferential running speed, subjects may have altered their running pattern to counteract this change. Due to the pace that was selected, lower forces could have been observed when compared to increased speeds. This could have decreased the possibility of observing differences in the forces observed. Furthermore, the biomechanics of treadmill running may differ from the biomechanics observed in an outdoor environment (Yong et al., 2014).

The direct measurement of internal JRFs during acute running does not indicate a significant difference between rearfoot and forefoot strike patterns. The implication of this finding supports the ideology of runner individuality and variability in which force patterns cannot be predicted in all runners, and therefore supports the multifactorial and individualistic nature of repetitive injury development. Similar strike patterns do not demonstrate significantly consistent joint forces between runners. Furthermore, the current study suggests no observable differences in joint kinetics between different strike patterns. This finding is important for the running community as transitioning away from a rearfoot strike pattern is a very common technique used to decrease potential for injury.

It is suggested that future research build on the previous acute study to observe long-term bouts of running and the joint forces observed between the foot strikes. Also, it would be beneficial to repeat this study with similar footwear provided to subjects. Past research has had few studies in which the footwear was controlled (Valenzuela et al., 2015). Therefore, future studies should consider offering identical footwear to subjects, if possible, in order to observe joint effects in a more common running method. Also, future research should be encouraged to observe chronic effects in joint forces from a forefoot transition as this study only focused on the acute observations. More importantly, it is essential to continue to investigate the effects that other variables, such as muscular weakness, gender, age, running age, pronation, mobility, running surface, footwear, or other controllable and uncontrollable factors might have on joint mechanics as well as the potential for injury development in runners (Phinyomark, Hettinga, Osis, & Ferber, 2014).

Acknowledgements

The researcher would like to thank Dr. David Titcomb for his leadership and guidance for this study, Liberty University graduate assistants Jonathan Houck and Austin Smith for their assistance with lab protocol and manual set-up of equipment, and all the subjects who volunteered their time.

References

Almeida, M. O., Davis, I. S., & Lopes, A. D. (2015). Biomechanical differences of foot-strike patterns during running: A systematic review with meta-analysis. *Journal of Orthopedic& Sports Physical Therapy, 45* (10), 738-755.

Almonroeder, T., Willson, J. D., & Kernozek, T. W. (2013). The Effect of Foot Strike Pattern on Achilles Tendon Load During Running. *Annals of Biomechical Engineering, 41* (8), 1758-1766.

Benson, L. C., & O'Conner, K. M. (2015). The effect of exertion on joint kinematics and kinetics during running using a waveform analysis approach. *Journal of Applied Biomechanics, 31* (4), 250-257.

Bishop, M., Fiolkowski, P., Conrad, B., Brunt, D., & Horodyski, M. (2006). Athletic footwear, leg stiffness, and running kinematics. *Journal of Athletic Training, 41*, (4), 387-392.

Boyer, E. R., Rooney, B. D., & Derrick, T. R. (2014). Rearfoot and midfoot or forefoot impacts in habitually shod runners. *Medicine & Science in Sports & Exercise, 46* (7), 1384-1391.

Breine, B., Malcolm, P., Frederick, E. C., & De Clercq, D. (2014). Relationship between running speed and initial foot contact patterns. *Medicine & Science in Sports & Exercise, 46* (8), 1595-1603.

Butler, R. J., Crowell III, H. P., & Davis, I. M. (2003). Lower extremity stiffness: Implications for performance and injury. *Clinical Biomechanics, 18* (6), 511-517.

Cavanagh, P. R., & Lafortune, M. A. (1980). GRFs in distance running. *Journal of Biomechanics, 13* (2), 397-406.

Cheung, R. T. & Davis, I. S. (2016). Landing pattern modification to improve patellofemoral pain in runners: A case series. *Journal of Orthopedic & Sports Physical Therapy, 41* (12), 914-919.

Daoud, A. I., Geissler, G. J., Wang, F., Saretsky, J., Daoud, Y. A., & Leiberman, D. E. (2012). Foot strike and injury rates in endurance runners: A retrospective study. *Medicine & Science in Sports & Exercise, 44* (7), 1325-1334.

Fredericks, W., Swank, S., Teisberg, M., Hampton, B., Ridpath, L. & Hanna, J. B. (2015). Lower extremity biomechanical relationships with different speeds in traditional, minimalist, and barefoot footwear. *Journal of Sports Science and Medicine, 14* (2), 276-283.

Golightly, Y. M., Hannan, M. T., Dufour, A. B., Hillstrom, H. J., & Jordan, J. M. (2014). Foot disorders associated with over-pronated and over-supinated foot function: The Johnston County Osteoarthritis Project. *Foot and Ankle International, 35* (11), 1159-1165.

Goss, D. L., Lewek, M., Yu, B., Ware, W. B., Teyhen, D. S., & Gross, M. T. (2015). Lower extremity biomechanics and self-reported foot-strike patterns among runners in traditional minimalist shoes. *Journal of Athletic Training, 50* (6), 603-611.

Houglum, P. A. & Bertoti D. B. (2012). *Brunnstrom's clinical kinesiology* (6th ed.). Philadelphia, PA: F. A. Davis Company.

Kuhman, D., Melcher, D., & Paquette, M. R. (2015). Ankle and knee kinetics between strike patterns at common training speeds in competitive male runners. *European Journal of Sport Science,* doi:10.1080/17461391.2015.1086818.

Kulmala, J., Avela, J., Pasanen, K., & Parkkari, J. (2013). Forefoot strikers exhibit lower running-induced knee loading than rearfoot strikers. *Medicine & Science in Sports & Exercise, 45* (12), 2306-2313.

Lieberman, D. E., Venkadesan, M., Werbel, W. A., Daoud, A. I., D'Andrea, S., Davis, I. S. (2010). Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature, 463* (7280), 531-535.

Mann, R., Malisoux, C., Nuhrenborger, A., Urhausen, A., Meijer, K., & Thelsen, D. (2015). Association of previous injury and speed with running style and stride-to-stride fluctuations. *Scandinavian Journal of Medicine & Science in Sports, 25* (6), 638-645.

Milner, C. E., Ferber, R., Pollard, C. D., Hamill, J. & Davis, I. S. (2006). Biomechanical factors associated with stress fracture in female runners. *Medicine & Science in Sports and Exercise, 38* (2), 323-328.

Paquette, M. R., Milner, C. E., & Melcher, D. A. (2016). Foot contact angle variability during a prolonged run with relation to injury history and habitual foot strike pattern. *Scandinavian Journal of Medicine & Science in Sports,* doi: 10.1111/sms.12647. http://onlinelibrary.wiley.com/doi/10.1111/sms.12647/abstract

Phinyomark, A., Hettinga, B. A., Osis, S. T., & Ferber, R. (2014). Gender and age-related differences in bilateral lower extremity mechanics during treadmill running. *PLOS, 9* (8), doi:10.1371/journal.pone.0105246.

Rabiei, M., Eslami, M., & Movaghar, A. F. (2016). The assessment of three-dimensional foot pronation using a principal component analysis method in the stance phase of running. *The Foot Journal, 29* (1), 11-17.

Rice, H. M., Jamison, S. T., & Davis, I. S. (2016). Footwear matters: Influence of footwear and strike pattern on load rates during running. *Medicine & Science in Sports & Exercise, 48* (12), 2462-2468.

Rooney, B. D., & Derrick, T. R. (2013). Joint contact loading in forefoot and rearfoot strike patterns during running. *Journal of Biomechanics, 46* (13), 2201-2206.

Sasimontonkul, S., Bay, B. K., & Pavol, M. J. (2007). Bone contact forces on the distal tibia during the stance phase of running. *Journal of Biomechanics, 40* (15), 3503-3509.

Schneck, D. J. & Bronzino, J. D. (Eds.). (2003). *Biomechanics: Principles and applications*. Boca Raton, FL: CRC Press.

Stearne, S. M., Alderson, J. A., Green, B. A., Donnelly, C. J., & Rubenson, J. (2014). Joint kinetics in rearfoot versus forefoot running: Implications of switching technique. *Medicine & Science in Sports & Exercise, 46* (8), 1578-1587.

Thompson, M. A., Lee, S. S., Seegmiller, J., & McGowan, C. P. (2015). Kinematic and kinetic comparison of barefoot and shod running in mid/forefoot and rearfoot strike runners. *Gait and Posture, 41* (4), 957-959.

Valenzuela, K. A., Lynn, S. K., Mikelson, L. R., Noffal, G. J., & Judelson, D. A. (2015). Effect of acute alterations in foot strike patterns during running on sagittal plane lower limb kinematics and kinetics. *Journal of Sports Science and Medicine, 14* (1), 225-232.

van Gent, R., Siem, D., van Middlekoop, M., van Os, A., Bierma-Zeinstra, S., & Koes, B. (2007) Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. *British Journal of Sports Medicine, 41* (8), 469-480.

Vannatta, C. N. & Kernozek, T. W. (2015). Patellofemoral joint stress during running with alterations in foot strike pattern. *Medicine & Science in Sports and Exercise, 47* (5), 1001-1008.

Williams, D. S., McClay, I. S., & Hamill, J. (2001). Arch structure and injury patterns in runners. *Clinical Biomechanics, 16* (4), 341-347.

Willson, J. D., Ratcliff, O. M., Meardon, S. A., & Willy, R. W. (2015). Influence of step length and landing pattern of patellofemoral joint kinetics during running. *Scandinavian Journal of Medicine and Science in Sports, 25* (6), 736-743.

Yong, J. R., Silder, A., & Delp, S. L. (2014). Differences in muscle activity between natural forefoot and rearfoot strikers during running. *Journal of Biomechanics, 47* (15), 3593-3597.

Appendix

Table 1

Participant demographics

	Male	Female	All
Measure	M (SD)	M (SD)	M (SD)
Height (cm)	177.46 (6.36)	165.00 (5.93)	171.23 (8.76)
Mass (kg)	77.94 (6.18)	57.85 (7.93)	67.90 (12.41)
Age (years)	34.1 (10.75)	25.00 (6.85)	29.55 (9.94)

Note. 10 male and 10 female subjects.

Table 2

Paired Samples Test p Values

Comparison	P value (all subjects)	P value (males only)	P value (females only)
RLHIPX – FLHIPX	.446	.383	.115
RRHIPX – FRHIPX	.137	.494	.110
RLHIPY – FLHIPY	.739	.859	.781
RRHIPY – FRHIPY	.735	.433	.272
RLHIPZ – FLHIPZ	.672	.149	.209
RRHIPZ – FRHIPZ	.290	.484	.319
RLKNEX – FLKNEX	.371	.779	.174
RRKNEX – FRKNEX	.305	.746	.278
RLKNEY – FLKNEY	.952	.452	.631
RRKNEY – FRKNEY	.443	.334	.220
RLKNEZ – FLKNEZ	.510	.332	.204
RRKNEZ – FRKNEZ	.275	.389	.364
RLANKX – FLANKX	.714	.215	.224
RRANKX – FRANKX	.763	.255	.352
RLANKY – FLANKY	.601	.087	.193
RRANKY – FRANKY	.667	.484	.308
RLANKZ – FLANKZ	.990	.873	.854
RRANKZ – FRANKZ	.802	.685	.390

Note. The first letter of each description designates rearfoot (R) or forefoot (F) condition; the second letter designates right (R) or left (L) side; the next three letters designate which joint is observed: hip (HIP), knee (KNE), or ankle (ANK); the last letter designates in which plane the forces were observed via Polygon software: hip and knee X plane = anterior/posterior; ankle X plane = compression/tension; hip, knee, and ankle Y plane = medial/lateral; hip and knee Z plane = compression/tension; ankle Z plane = anterior/posterior.

Table 3

Force Characteristics for all Subjects

Force	Maximum	Minimum	Range	Mean (SD)
RLHIPX	-3.916	-8.598	4.682	-6.117 (1.296)
FLHIPX	-2.764	-9.224	6.460	-5.865 (1.588)
RRHIPX	-3.812	-8.498	4.686	-6.236 (1.269)
FRHIPX	2.182	-9.590	11.772	-5.474 (2.650)
RLHIPY	3.898	-4.490	8.388	.805 (2.663)
FLHIPY	4.082	-4.346	8.428	.746 (2.562)
RRHIPY	4.022	-9.820	13.842	-1.819 (3.030)
FRHIPY	3.850	-21.100	24.950	-2.250 (4.956)
RLHIPZ	-10.79	-21.46	10.67	-16.624 (2.913)
FLHIPZ	-4.238	-24.500	20.262	-16.266 (4.811)
RRHIPZ	-7.64	-21.38	13.74	-16.457 (3.306)
FRHIPZ	11.320	-24.180	35.500	-14.513 (7.874)
RLKNEX	11.120	3.372	7.748	8.135 (2.619)
FLKNEX	12.780	1.926	10.854	7.628 (3.102)
RRKNEX	11.560	2.324	9.236	8.166 (2.692)
FRKNEX	13.020	1.118	11.902	7.340 (3.642)
RLKNEY	7.510	-3.706	11.216	2.566 (3.064)
FLKNEY	6.838	-2.540	9.378	2.587 (2.627)
RRKNEY	3.844	-6.212	10.056	-2.781 (2.521)
FRKNEY	3.286	-21.380	24.666	-3.584 (4.729)
RLKNEZ	-11.98	-22.38	10.40	-17.199 (2.559)
FLKNEZ	-6.29	-25.30	19.01	-16.743 (4.208)
RRKNEZ	-8.626	-21.580	12.954	-16.795 (2.936)
FRKNEZ	23.700	-24.580	48.280	-14.166 (9.982)
RLANKX	25.16	12.94	12.22	19.231 (3.166)
FLANKX	28.520	7.284	21.236	18.930 (4.912)
RRANKX	24.360	9.326	15.034	18.969 (3.557)
FRANKX	27.220	5.748	21.472	18.727 (5.475)
RLANKY	5.314	-2.836	8.150	2.011 (2.347)
FLANKY	5.218	-2.232	7.450	2.265 (2.176)
RRANKY	3.822	-4.254	8.076	-1.473 (2.402)
FRANKY	3.390	-4.238	7.628	-1.322 (2.157)
RLANKZ	10.428	-5.332	15.760	5.132 (4.071)
FLANKZ	8.608	2.016	6.592	5.142 (2.092)
RRANKZ	10.692	-6.190	16.882	5.036 (3.589)
FRANKZ	10.328	1.896	8.432	4.855 (2.243)

Note. Forces expressed in terms of body weight; the first letter of each description designates rearfoot (R) or forefoot (F) condition; the second letter designates right (R) or left (L) side; the next three letters designate which joint is observed: hip (HIP), knee (KNE), or ankle (ANK); the last letter designates in which plane the forces were observed via Polygon software: hip and knee X plane = anterior/posterior; ankle X plane = compression/tension; hip, knee, and ankle Y plane = medial/lateral; hip and knee Z plane = compression/tension; ankle Z plane = anterior/posterior; negative and positive numbers indicate direction: hip X (- implies posterior, + implies anterior); left hip Y (- implies medial, + implies lateral); right hip Y (- implies lateral, + implies medial); hip Z (- implies compression, + implies tension); knee X (- implies posterior, + implies anterior); left knee Y (- implies medial, + implies lateral); right knee Y (- implies lateral, + implies medial); knee Z (- implies compression, + implies tension); ankle X (- implies compression, + implies tension); ankle Y (- implies lateral, + implies medial); ankle Z (- implies posterior, + implies anterior).

Table 4

Force Characteristics for Only Male Subjects

Force	Maximum	Minimum	Range	Mean (SD)
RLHIPX	-3.916	-8.280	4.364	-5.786 (1.215)
FLHIPX	-2.764	-9.224	6.460	-6.057 (1.824)
RRHIPX	-4.030	-7.518	3.488	-6.032 (1.000)
FRHIPX	2.182	-9.008	11.190	-5.279 (3.456)
RLHIPY	3.898	-4.120	8.018	1.342 (2.566)
FLHIPY	4.082	-3.092	7.174	1.306 (2.476)
RRHIPY	2.408	-4.342	6.750	-1.623 (2.290)
FRHIPY	1.906	-21.100	23.006	-3.748 (6.835)
RLHIPZ	-11.39	-21.04	9.65	-16.123 (3.135)
FLHIPZ	-13.260	-21.660	8.400	-17.478 (2.781)
RRHIPZ	-12.36	-21.38	9.02	-16.716 (3.101)
FRHIPZ	11.320	-21.180	32.500	-14.062 (9.751)
RLKNEX	11.120	3.372	7.748	7.901 (3.334)
FLKNEX	12.780	3.736	9.044	8.503 (2.771)
RRKNEX	11.560	3.816	7.744	7.932 (2.770)
FRKNEX	13.020	1.118	11.902	7.755 (3.568)
RLKNEY	4.272	-3.430	7.702	1.720 (2.699)
FLKNEY	5.532	-2.540	8.072	2.140 (2.950)
RRKNEY	3.844	-5.402	9.246	-1.722 (2.456)
FRKNEY	3.286	-21.380	24.666	-4.075 (6.907)
RLKNEZ	-13.08	-21.38	8.30	-16.969 (2.685)
FLKNEZ	-13.96	-21.76	7.80	-17.767 (2.443)
RRKNEZ	-14.120	-21.580	7.460	-17.322 (2.603)
FRKNEZ	23.700	-20.040	43.740	-12.802 (13.825)
RLANKX	23.50	13.80	9.70	18.793 (3.325)
FLANKX	24.260	15.680	8.580	20.093 (2.868)
RRANKX	24.360	15.280	9.080	19.276 (3.258)
FRANKX	24.900	17.140	7.760	20.338 (2.856)
RLANKY	4.052	-2.836	6.888	1.144 (2.519)
FLANKY	5.102	-1.880	6.982	2.628 (2.217)
RRANKY	3.822	-3.540	7.362	-.769 (2.649)
FRANKY	3.390	-4.238	7.628	-1.242 (2.227)
RLANKZ	9.582	-5.332	14.914	5.308 (4.846)
FLANKZ	8.608	2.748	5.860	5.559 (2.325)
RRANKZ	9.684	-6.190	15.874	4.124 (4.519)
FRANKZ	7.524	2.444	5.080	5.027 (1.864)

Note. Forces expressed in terms of body weight; the first letter of each description designates rearfoot (R) or forefoot (F) condition; the second letter designates right (R) or left (L) side; the next three letters designate which joint is observed: hip (HIP), knee (KNE), or ankle (ANK); the last letter designates in which plane the forces were observed via Polygon software: hip and knee X plane = anterior/posterior; ankle X plane = compression/tension; hip, knee, and ankle Y plane = medial/lateral; hip and knee Z plane = compression/tension; ankle Z plane = anterior/posterior; negative and positive numbers indicate direction: hip X (- implies posterior, + implies anterior); left hip Y (- implies medial, + implies lateral); right hip Y (- implies lateral, + implies medial); hip Z (- implies compression, + implies tension); knee X (- implies posterior, + implies anterior); left knee Y (- implies medial, + implies lateral) ; right knee Y (- implies lateral, + implies medial); knee Z (- implies compression, + implies tension); ankle X (- implies compression, + implies tension); ankle Y (- implies lateral, + implies medial); ankle Z (- implies posterior, + implies anterior).

Table 5

Force Characteristics for Only Female Subjects

Force	Maximum	Minimum	Range	Mean (SD)
RLHIPX	-4.746	-8.598	3.852	-6.484 (1.386)
FLHIPX	-3.330	-8.360	5.030	-5.644 (1.499)
RRHIPX	-3.812	-8.498	4.686	-6.484 (1.535)
FRHIPX	-2.754	-9.590	6.836	-5.578 (2.026)
RLHIPY	3.528	-4.490	8.018	.742 (2.620)
FLHIPY	3.298	-4.346	7.644	.672 (2.458)
RRHIPY	4.022	-9.820	13.842	-2.391 (3.547)
FRHIPY	3.850	-3.740	7.590	-1.348 (2.229)
RLHIPZ	-10.79	-21.46	10.67	-17.111 (2.942)
FLHIPZ	-4.238	-24.500	20.262	-15.248 (6.269)
RRHIPZ	-7.64	-19.96	12.32	-16.362 (3.772)
FRHIPZ	-3.954	-24.180	20.226	-14.965 (6.776)
RLKNEX	10.178	3.452	6.726	8.133 (2.009)
FLKNEX	10.760	1.926	8.834	6.913 (3.479)
RRKNEX	11.440	2.324	9.116	8.400 (2.890)
FRKNEX	11.720	1.270	10.450	7.137 (4.018)
RLKNEY	7.510	-3.706	11.216	3.236 (3.470)
FLKNEY	6.838	-2.494	9.332	2.951 (2.545)
RRKNEY	2.076	-6.080	8.156	-3.391 (2.283)
FRKNEY	1.196	-4.832	6.028	-2.958 (1.936)
RLKNEZ	-11.98	-22.38	10.40	-17.452 (2.696)
FLKNEZ	-6.29	-25.30	19.01	-15.895 (5.492)
RRKNEZ	-8.626	-20.900	12.274	-16.487 (3.390)
FRKNEZ	-5.352	-24.580	19.228	-15.393 (6.078)
RLANKX	25.16	12.94	12.22	19.668 (3.303)
FLANKX	28.520	7.284	21.236	17.980 (6.416)
RRANKX	22.660	9.326	13.334	18.857 (4.107)
FRANKX	27.220	5.748	21.472	17.515 (7.154)
RLANKY	5.314	-2.140	7.454	2.695 (2.149)
FLANKY	5.218	-2.232	7.450	1.930 (2.318)
RRANKY	2.428	-4.254	6.682	-1.868 (2.153)
FRANKY	2.408	-4.140	6.548	-1.275 (2.290)
RLANKZ	10.428	-3.806	14.234	4.637 (3.543)
FLANKZ	7.814	2.016	5.798	4.845 (2.025)
RRANKZ	10.692	2.808	7.884	5.702 (2.730)
FRANKZ	10.328	1.896	8.432	4.879 (2.673)

Note. Forces expressed in terms of body weight; the first letter of each description designates rearfoot (R) or forefoot (F) condition; the second letter designates right (R) or left (L) side; the next three letters designate which joint is observed: hip (HIP), knee (KNE), or ankle (ANK); the last letter designates in which plane the forces were observed via Polygon software: hip and knee X plane = anterior/posterior; ankle X plane = compression/tension; hip, knee, and ankle Y plane = medial/lateral; hip and knee Z plane = compression/tension; ankle Z plane = anterior/posterior; negative and positive numbers indicate direction: hip X (- implies posterior, + implies anterior); left hip Y (- implies medial, + implies lateral); right hip Y (- implies lateral, + implies medial); hip Z (- implies compression, + implies tension); knee X (- implies posterior, + implies anterior); left knee Y (- implies medial, + implies lateral); right knee Y (- implies lateral, + implies medial); knee Z (- implies compression, + implies tension); ankle X (- implies compression, + implies tension); ankle Y (- implies lateral, + implies medial); ankle Z (- implies posterior, + implies anterior).

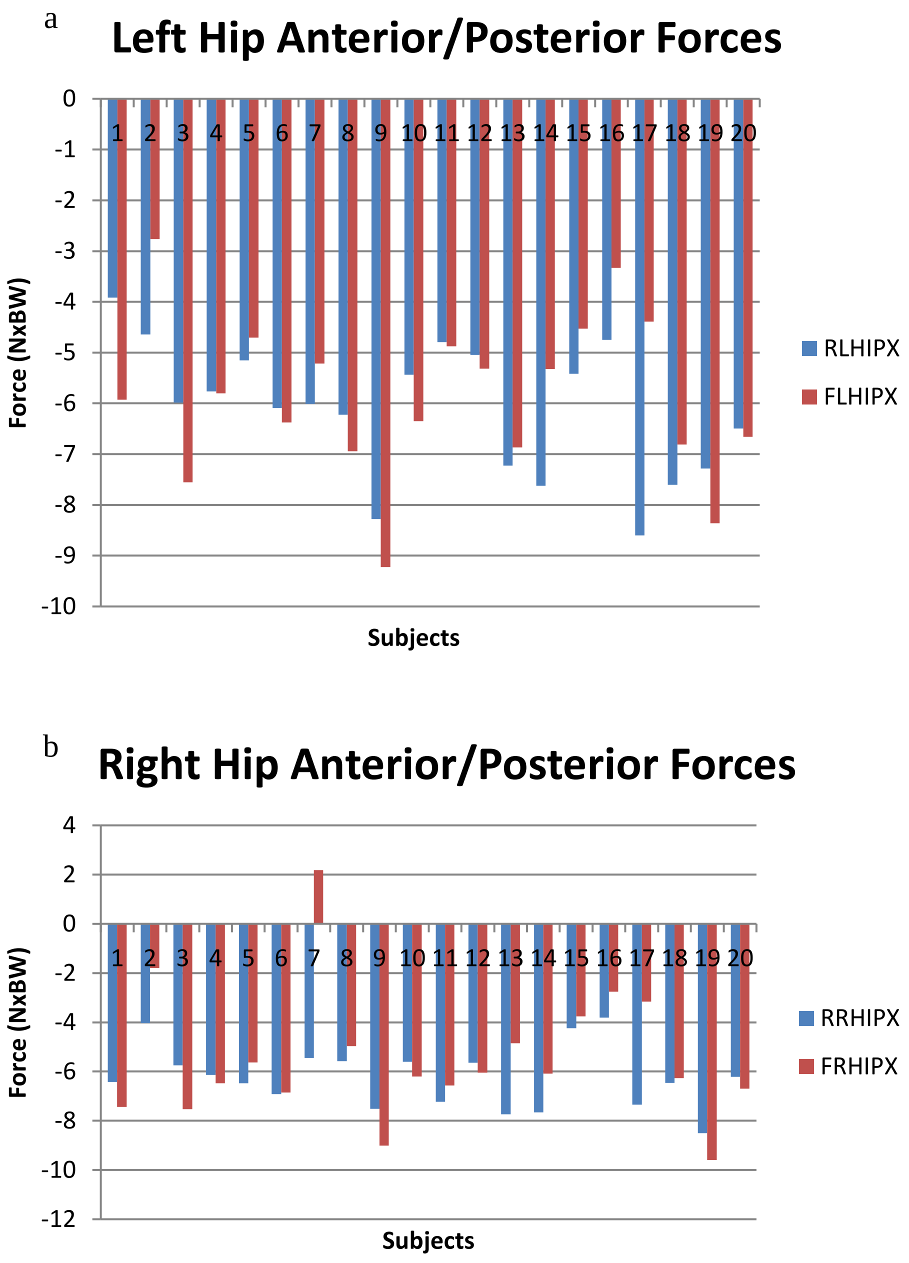
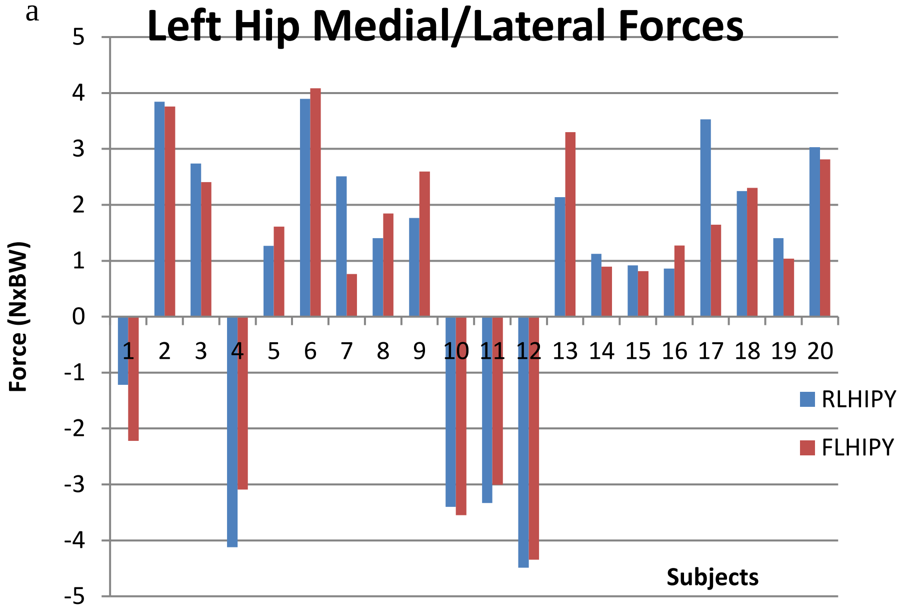


Figure 1. Forces shown are the average of the peak forces observed in five steps. Part (a) demonstrates forces observed in the left hip and part (b) demonstrates forces observed in the right hip. Positive values designate forces in the anterior direction and negative values designate forces in the posterior direction (subjects 1-10 are males, 11-20 are females).

a



b

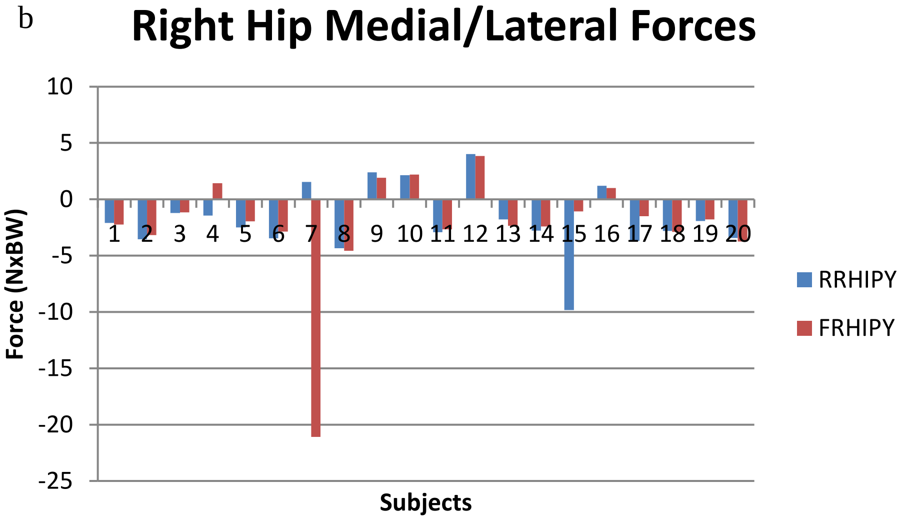
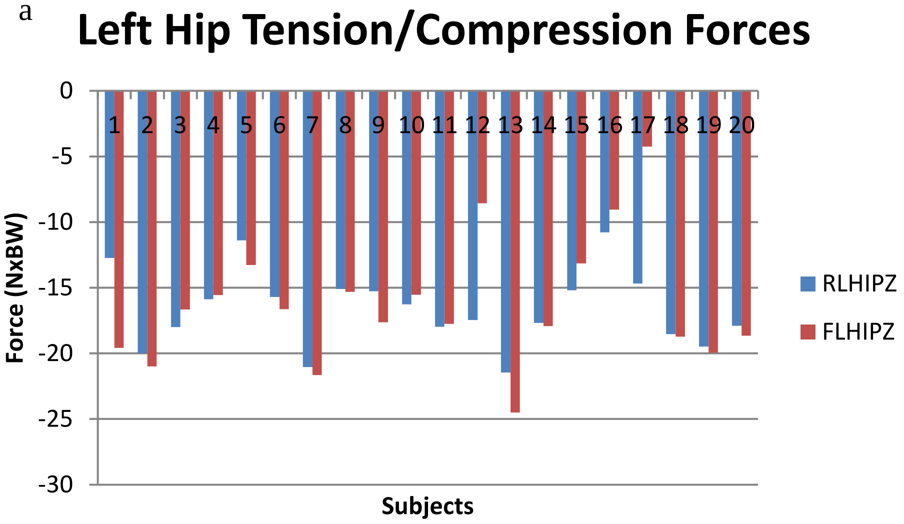


Figure 2. Forces shown are the average of the peak forces observed in five steps. Part (a) demonstrates forces observed in the left hip and part (b) demonstrates forces observed in the right hip. Positive values for (a) designate forces in the lateral direction and negative values for (a) designate forces in the medial direction. Positive values for (b) designate forces in the medial direction and negative values for (b) designate forces in the lateral direction (subjects 1-10 are males, 11-20 are females).

a



b

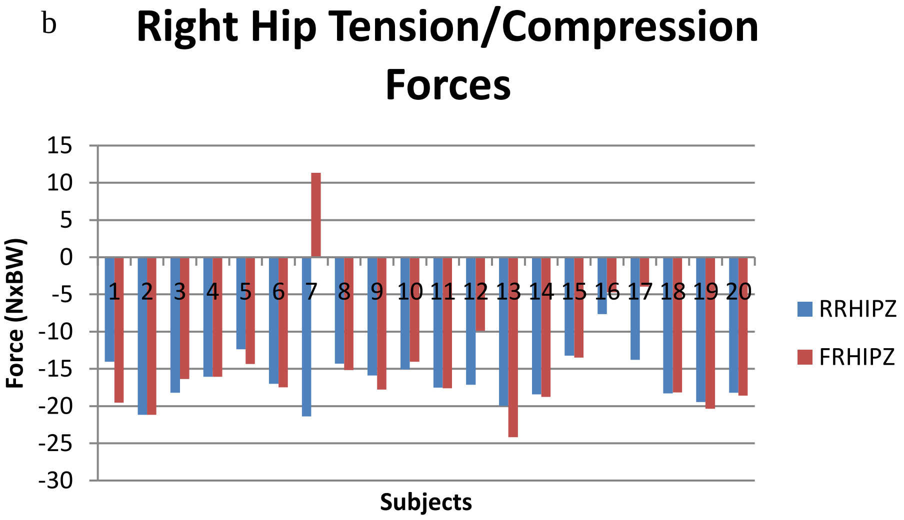


Figure 3. Forces shown are the average of the peak forces observed in five steps. Part (a) demonstrates forces observed in the left hip and part (b) demonstrates forces observed in the right hip. Positive values designate tensile forces and negative values designate compression forces (subjects 1-10 are males, 11-20 are females).

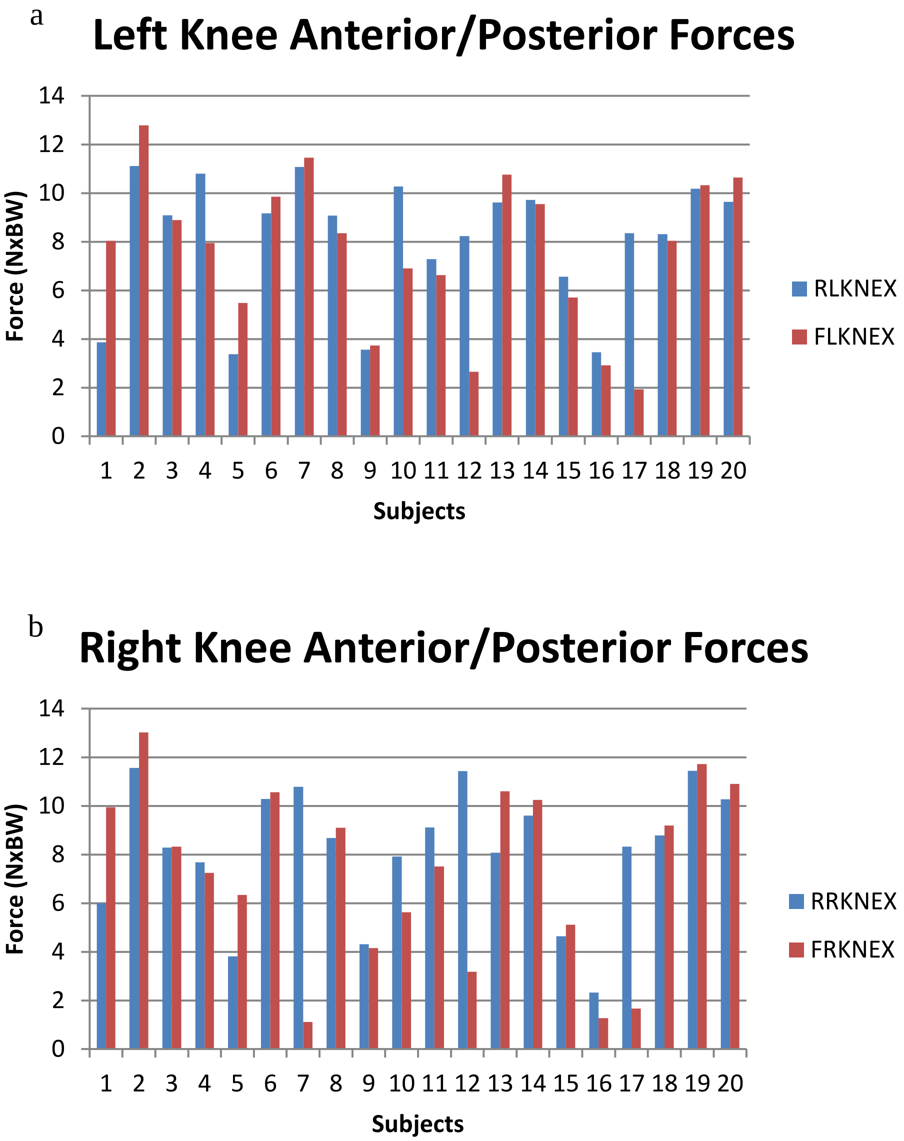


Figure 4. Forces shown are the average of the peak forces observed in five steps. Part (a) demonstrates forces observed in the left knee and part (b) demonstrates forces observed in the right knee. Positive values designate forces in the anterior direction and negative values designate forces in the posterior direction (subjects 1-10 are males, 11-20 are females).

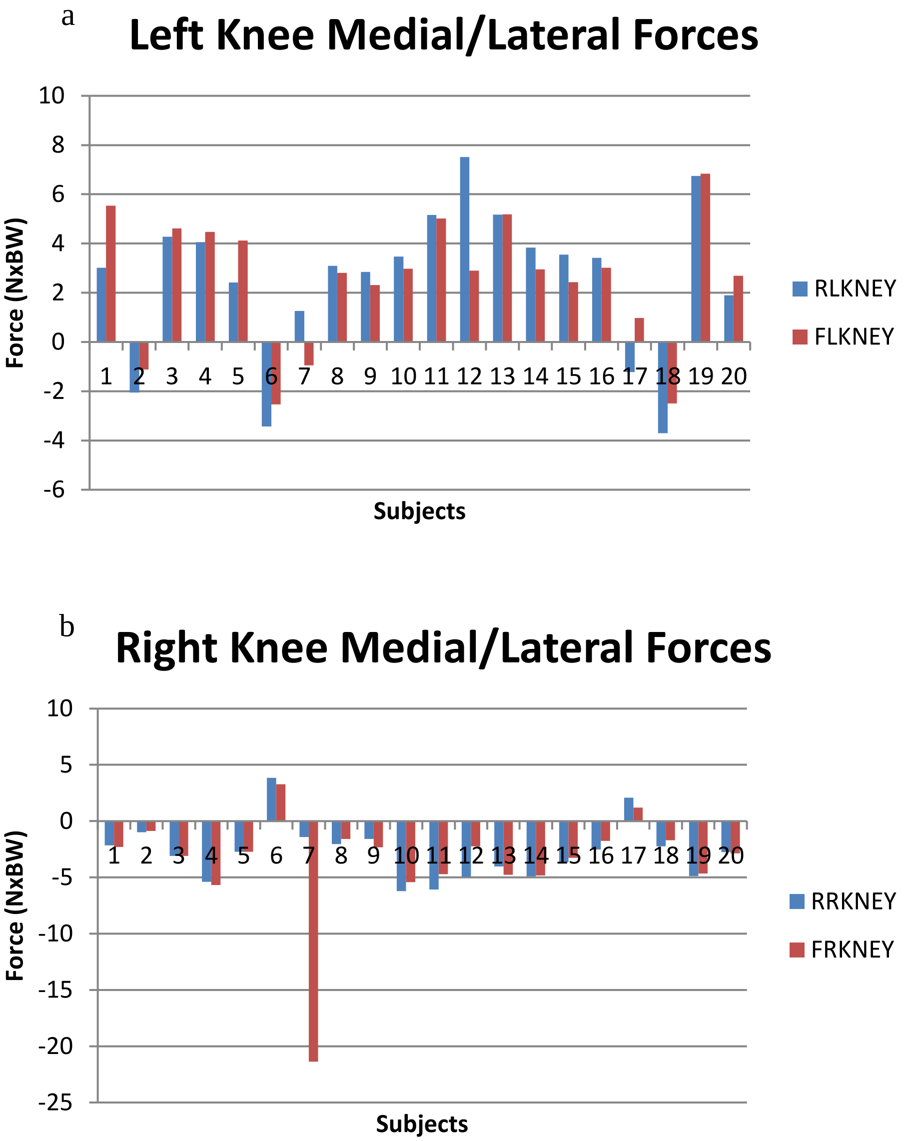


Figure 5. Forces shown are the average of the peak forces observed in five steps. Part (a) demonstrates forces observed in the left knee and part (b) demonstrates forces observed in the right knee. Positive values for (a) designate forces in the lateral direction and negative values for (a) designate forces in the medial direction. Positive values for (b) designate forces in the medial direction and negative values for (b) designate forces in the lateral direction (subjects 1-10 are males, 11-20 are females).

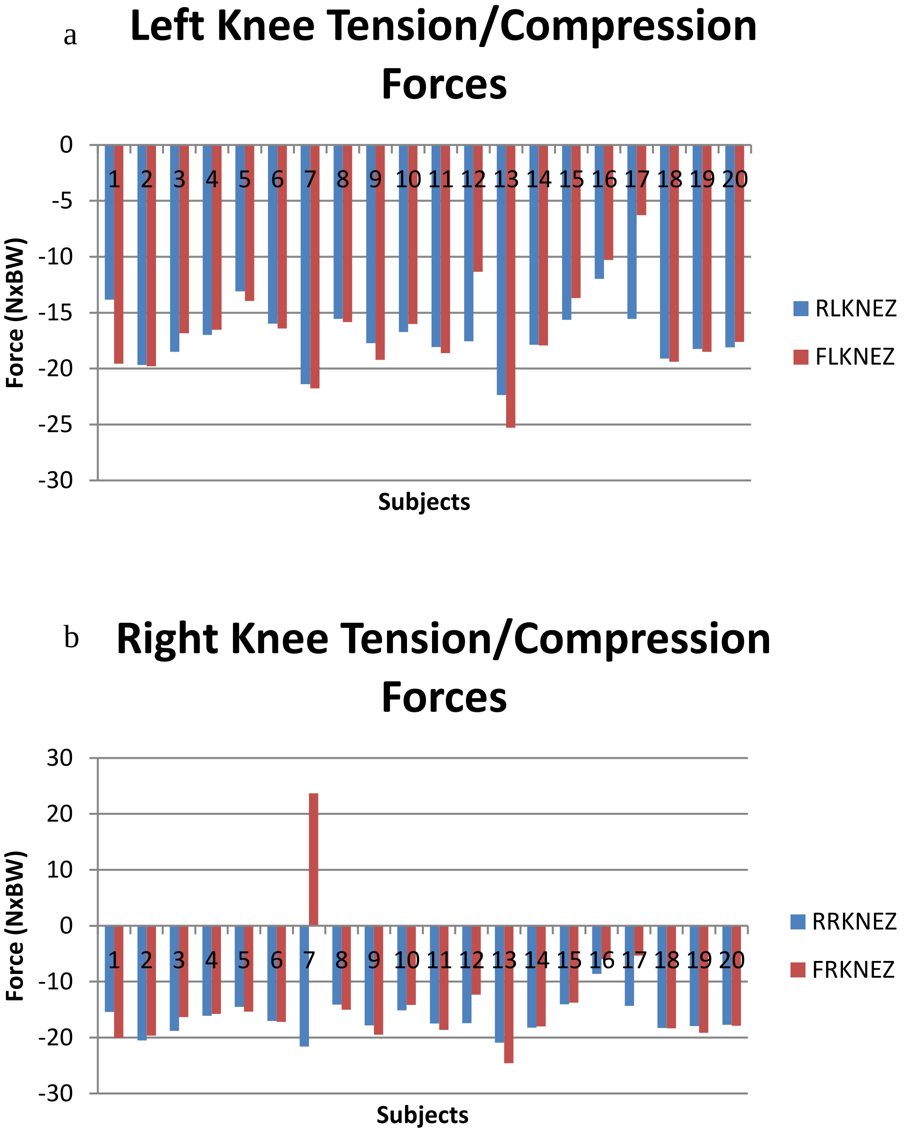


Figure 6. Forces shown are the average of the peak forces observed in five steps. Part (a) demonstrates forces observed in the left knee and part (b) demonstrates forces observed in the right knee. Positive values designate tensile forces and negative values designate compressive forces (subjects 1-10 are males, 11-20 are females).

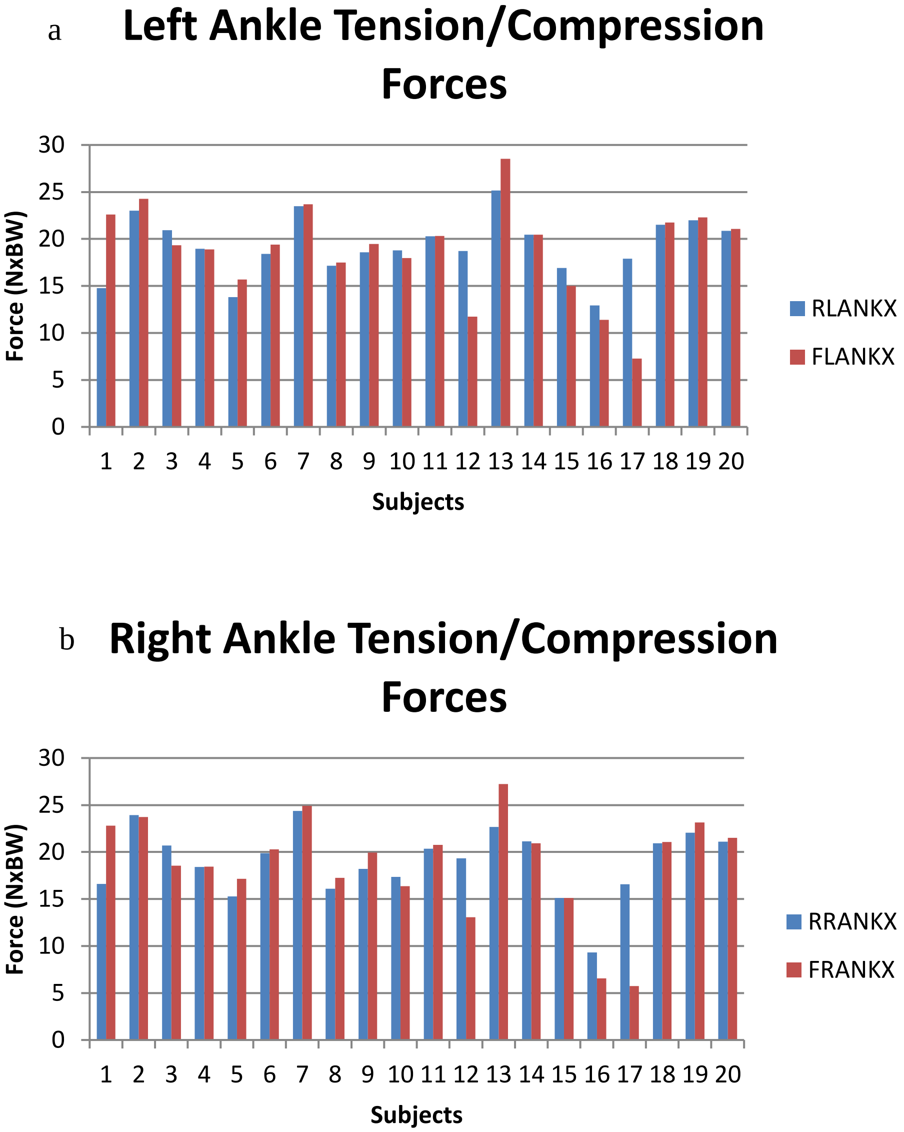


Figure 7. Forces shown are the average of the peak forces observed in five steps. Part (a) demonstrates forces observed in the left ankle and part (b) demonstrates forces observed in the right ankle. Positive values designate tensile forces and negative values designate compressive forces (subjects 1-10 are males, 11-20 are females).

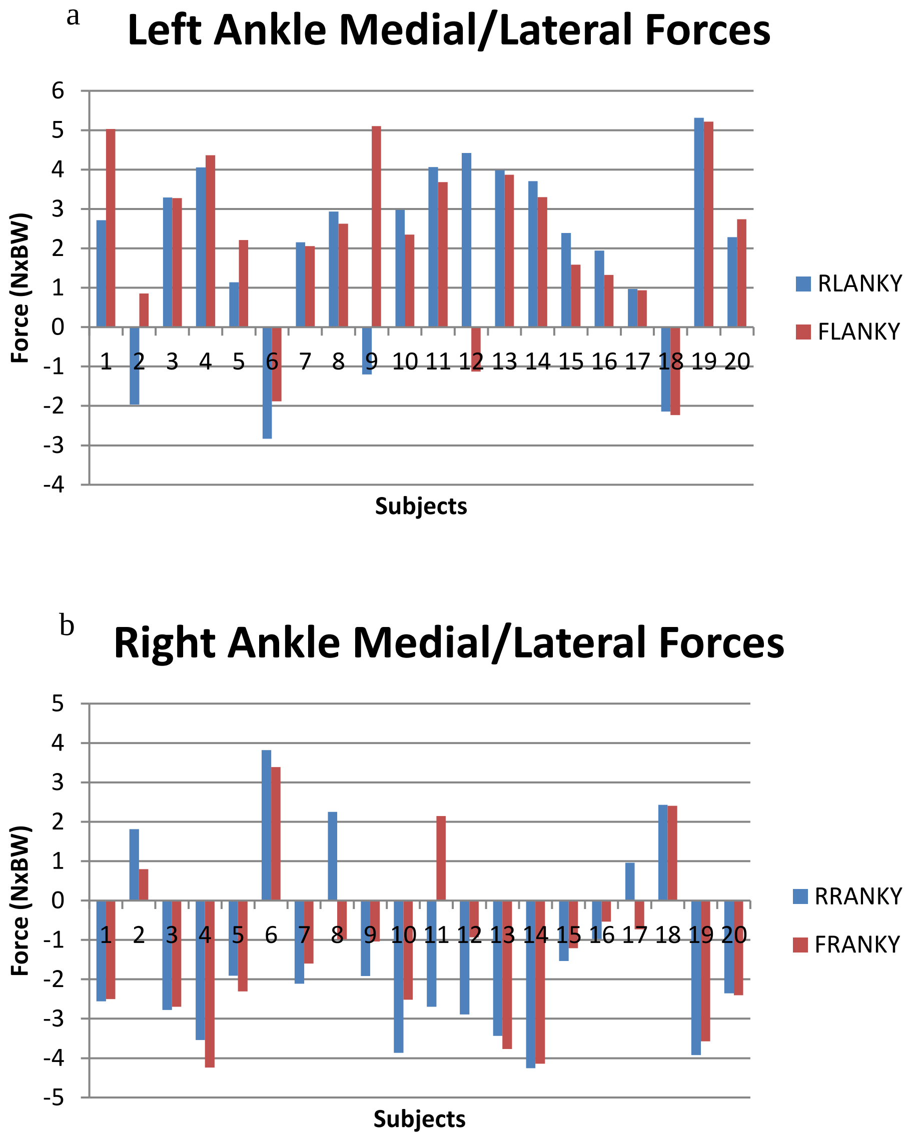
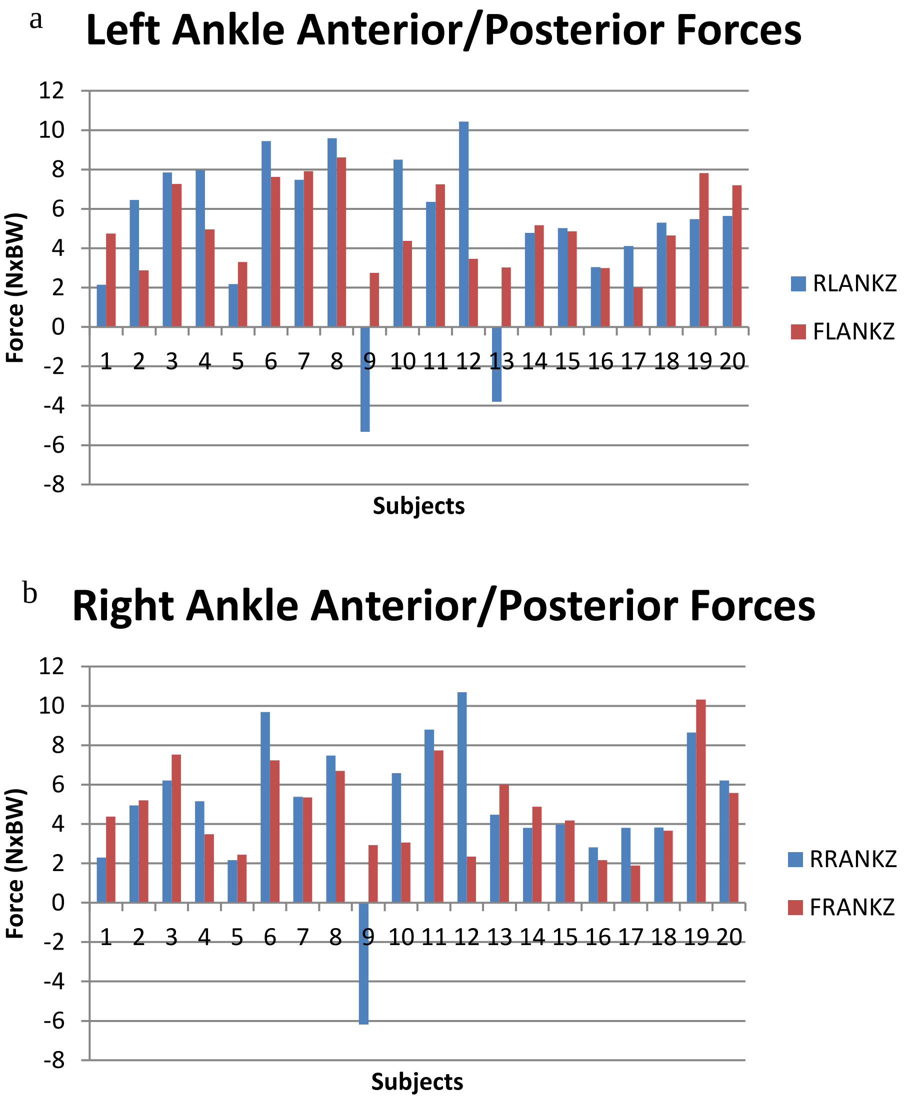


Figure 8. Forces shown are the average of the peak forces observed in five steps. Part (a) demonstrates forces observed in the left ankle and part (b) demonstrates forces observed in the right ankle. Positive values designate forces in the medial direction and negative values designate forces in the lateral direction (subjects 1-10 are males, 11-20 are females).



Left Ankle Anterior/Posterior Forces

Right Ankle Anterior/Posterior Forces

Figure 9. Forces shown are the average of the peak forces observed in five steps. Part (a) demonstrates forces observed in the left ankle and part (b) demonstrates forces observed in the right ankle. Positive values designate forces in the anterior direction and negative values designate forces in the posterior direction (subjects 1-10 are males, 11-20 are females).