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Ground Reaction Force Characteristics Associated with Modified Short-leg Walkers

A Thesis Presented for
the Master of Science
Degree
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ABSTRACT

Background. Although short-leg walkers are often used in the treatment of lower extremity injuries, little is known about the effect that the short-leg walker has on gait characteristics. The purpose of this study was to examine two different short-leg walkers and how heel height differences in the walker and shoe side may affect ground reaction forces (GRFs) and the effects of heel height modification in walker and/or shoe side on GRFs in walking.

Methods. A force platform was used to collect ground reaction force data on 10 healthy participants. Five trials in each of six conditions were performed by each participant: shoe, Gait Walker, Gait Walker with heel insert, Gait Walker modified, Equalizer, and Equalizer with heel insert.

Findings. A 2×6 (side $\times$ condition) analysis of variance (ANOVA) was completed on selected GRF variables ($P < 0.05$). The application of a walker created a peak GRF prior to the normal peaks associated with the loading response in both vertical and anteroposterior GRFs. Wearing a walker introduced an elevated minimum vertical GRF in all conditions except the Equalizer Walker when compared to Shoe on the shoe side. Peak propulsive GRFs were smaller in all five walker conditions compared to Shoe on walker side.

Interpretation. The application of heel insert in Gait Walker with heel insert (on shoe side) and Gait Walker modified (on walker side) does not diminish the minimum vertical GRF as hypothesized. Wearing a walker decreases the peak propulsive GRF on the walker side and induces asymmetrical loading.

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CHAPTER I

INTRODUCTION

Lower leg immobilization is necessary for the treatment of numerous injuries: ankle sprains, ankle and foot fractures, post surgical stabilization, and in the treatment of neuropathic foot ulcers (Crincoli and Trepman, 2001; Pollo et al., 1999; Zhang et al., 2006). In the past, synthetic total contact casts were the primary method used to immobilize the lower leg. It has become a norm to use short-leg walkers instead in these treatments. Short-leg walkers provide multiple benefits over total contact casts, which include decreased cost, ease of removal for cleaning or exercises, and recent studies have shown that they may produce fewer adverse effects on gait patterns and ankle musculature than a total contact cast (Pollo et al., 1999; Neumann et al., 1989).

Research regarding short-leg walkers has typically examined the plantar pressure during gait (Baumhauer et al., 1997; Crenshaw et al., 2004; Pollo et al., 2003). Plantar pressure data is important as it relates to neuropathic foot ulcers in diabetics. Diabetes affects nearly 15% of the population over 65 years old in developed countries (Cavanagh et al., 1981). A common consequence of diabetes is distal sensory neuropathy, which often leads to foot ulcers (Cavanagh et al., 1981). It has been found that short-leg walkers decrease plantar pressure better than a total contact cast (Baumhauer et al., 1997; Crenshaw et al., 2004; Pollo et al., 2003).

With the application of a short-leg walker, an artificial limb length discrepancy is imposed. Limb length discrepancy has been associated with asymmetrical loading during gait (White et al., 2004). However, there is still debate regarding the similarities between

true limb length discrepancy and artificial limb length discrepancy as well as which limb is receiving more of the load (White et al., 2004). Compensatory techniques, such as pelvic tilting and knee and hip flexion (Walsh et al., 2000), are used with a limb length discrepancy. Zhang et al. (2006) suggests that the imposed artificial limb length discrepancy created by a short-leg walker may affect gait patterns and ground reaction forces (GRFs). The duration of short-leg walker use may reach up to six months (Zhang et al., 2006), which may further exacerbate adverse effects due to abnormal patterns in GRFs and gait kinematics/kinetics. Research on biomechanical gait patterns in short-leg walkers has been very limited. Pollo et al. (1999) examined gait patterns in normal shoes, total contact cast, and a short-leg walker and found that short-leg walkers produced fewer adverse effects during gait than the total contact cast. Zhang et al. (2006) examined two different brands of short-leg walkers as compared to normal shoes. Both walkers also restricted movement in the frontal plane, by limiting ankle eversion. Zhang et al. (2006) and Pollo et al. (1999) also found that a greater demand was placed on the knee extensors with a decrease in knee adductor activity in the short-leg walkers. Zhang et al. (2006) found that the Equalizer walker simulated normal walking better than the Gait Walker. It was suggested that the different heel-to-forefoot differences that are seen between the two walkers allowed the Equalizer to simulate walking better than the Gait Walker (Zhang et al., 2006).

Ground reaction forces in short-leg walkers have only been reported in one study (Zhang et al., 2006). The peak GRFs associated with normal walking were not altered with the application of a short-leg walker. However, a small initial peak in GRF was observed during early stance phase. The Gait Walker also introduced an elevated portion

of the GRF curve during midstance. It was suggested that the sole design of the short-leg walker might contribute to this elevation. The Equalizer had a slightly greater curve throughout the outsole while the Gait Walker had a flatter curve (Zhang et al., 2006). To the knowledge of the author, no studies have investigated the effects of the artificial limb length discrepancy introduced with the use of a short-leg walker on GRFs and other biomechanical characteristics in gait. Therefore, further research is warranted in this area.

The purposes of this study were to investigate how heel height differences in the walker and shoe side may affect GRFs when wearing a short-leg walker and the effects of heel height modification in walker and/or shoe side on GRFs in walking. Inserts were made for the shoe side to eliminate the limb length discrepancy that was imposed by the application of a walker. An insert was also made to be applied to the Gait Walker so that heel-to-forefoot ratio could be increased and mimic the ratio seen in the Equalizer, which has been suggested to better facilitate gait (Zhang et al., 2006).

Hypothesis

The following hypotheses were tested:

1. The application of short-leg walkers would introduce an initial peak in GRF in gait.
2. Decreasing the artificial limb length discrepancy that is imposed by applying the short-leg walker with an insert on the shoe side would decrease or eliminate the initial peak GRF and reduce the GRF level during midstance.
3. A greater heel-to-forefoot difference would also eliminate the initial peak GRF and reduce the GRF level during midstance.

Delimitations

This study had the following delimitations:

1. Ten apparently healthy subjects were selected from a convenience sample of students and community members surrounding the University of Tennessee, Knoxville. Each subject was free from prior major lower extremity injuries.
2. Each subject performed five trials in all six conditions. Short-leg walkers were worn on the right side while a running shoe was worn on the left side.
3. GRF data was collected for 3 seconds bilaterally during each trial using two force platforms (1200 Hz, AMTI, MA).

Limitations

This study had the following limitations:

1. All subjects were selected from a convenience sample surrounding the University of Tennessee, Knoxville. All subjects were healthy and did not require the use of a short-leg walker.
2. Differences in the two short-leg walkers used in the study may be related to the differences in their outsole designs.
3. Errors may occur due to the limitations in the motion capture system during data collection process. However, every effort was made to complete the process adherent to sound biomechanical principles and practices and strict instructions of the manufacturers.

Assumption

This study had the following assumption: each subject had symmetrical walking between the left and right sides.

CHAPTER II

LITERATURE REVIEW

The main objective of this study was to examine the effects of heel height differences in the walker and shoe side and heel height modifications in the walker and/or shoe side on GRF patterns in walking. Several variables associated with GRFs, plantar pressure, and kinematic and kinetic data have been related to gait patterns wearing short-leg walkers. GRF patterns were therefore investigated in the current study. Literature regarding the benefits of short-leg walkers, GRFs, limb length discrepancy, heel height, and kinematics and kinetics of short-leg walkers will be reviewed in this chapter.

Benefits of Short-leg Walkers

Short-leg walkers are becoming more prevalent in the treatment of multiple lower extremity injuries. Short-leg walkers do not limit mobility as much as total contact casts that have been the main form of previous treatments (Armstrong et al., 2001). Short-leg walkers have been indicated in the treatment of ankle and foot fractures, severe ankle sprains, post surgical stabilization, neuropathic foot ulcerations (Pollo et al., 1999; Zhang et al., 2006). Although short-leg walkers may not produce the same degree of immobilization as a total contact cast, their benefits may outweigh this disparity between short-leg walkers and total contact casts (Pollo et al., 1999). Short-leg walkers allow easy access for cleaning or exercises, are less expensive, and have fewer adverse effects on kinematic and kinetic gait patterns than total contact casts (Pollo et al., 1999; Zhang et al., 2006; Pollo et al., 2003).

Short-leg walkers may appear to produce greater benefits than total contact casts, however, this can vary greatly depending on the brand that is being used. There is not a standard design for short-leg walkers. Differences can be found with regards to heel height, sole design, weight, and materials used in short-leg walkers. These differences may complicate recovery due to the extended amount of time (up to six months) that short-leg walkers can be worn (Pollo et al., 1999). Compensation by the contralateral limb may produce adverse effects on gait patterns and recovery.

Ground Reaction Forces

The typical GRF curve that is associated with normal walking includes two functions: the support of body weight and the acceleration of the body (Collins and Whittle, 1989). These two components are identified by the two vertical GRF peaks where the first peak is related to load acceptance and the second peak is associated with push off. The valley between these two peaks occurs at midstance of a gait cycle.

The loading rate is another variable that has been studied during normal walking. Collins and Whittle (1989) examined the relationship between the loading rate and three gait parameters: cadence, stride length, and velocity. Loading rate was calculated from the initial slope of the GRF curve. Thirteen male subjects participated in this study. Each was instructed to walk at a self-selected normal pace and then at two speeds above and two speeds below their normal pace. The velocity had the highest correlation with the loading rate and the stride length had the lowest correlation (Collins and Whittle, 1989). The results from this study suggest that the initial loading phase is similar across the subjects tested. The positive correlation between velocity and loading rate was significant. However, the actual walking speed was not monitored. It would be

interesting to see if each subject maintained similar loading rates at similar velocities. Typically, the application of a short-leg walker would cause a reduction in gait velocity. From this study, one may think that loading rate would demonstrate a corresponding decrease. This study also illustrated that walking speed needs to be monitored when comparisons of GRFs with and without lower limb devices are completed.

There has been limited research regarding GRFs in short-leg walkers. To the author's knowledge, only one study has been published regarding GRFs in short-leg walkers. Zhang et al. (2006) examined the GRFs, kinematics, and kinetics of two short-leg walkers (Gait Walker and Equalizer Walker) compared to a normal shoe condition in eleven subjects. Each subject performed five level walking trials in the three randomized conditions. Walking speed was monitored throughout testing to ensure a constant speed ($\pm 10\%$) for all conditions. Short-leg walkers were always applied to the right side of the body.

An initial peak prior to the peak in normal walking was observed in the ground reaction force data in the short-leg walkers. There was also an elevated portion during midstance associated with normal walking in the Gait Walker (Zhang et al., 2006). The authors proposed that this may be related to the sole design of the short-leg walker. A proper ratio between heel and forefoot heights may facilitate rollover from heel-strike to toe-off due to a lack of ankle movements wearing a walker. This elevated midstance of the ground reaction force was only seen in the Gait Walker, which had a smaller ratio of heel-to-forefoot height than the proposed ratio. The Equalizer had a greater ratio and the elevated portion of the ground reaction force was not seen (Zhang et al., 2006).

Pollo et al. (1999) investigated the kinematics and kinetics associated with four different short-leg walkers, a total contact cast, and normal shoes. Ten subjects participated in this study. Each subject participated in five level walking trials in the six randomized conditions (four short-leg walkers, synthetic cast, and normal shoes). Application side was also randomized for each subject. Pollo et al. (1999) found that the sole design of two walkers (curved, hard rubber sole) may tend to increase the knee flexion angle and possibly increase the posterior GRF. However, GRF data was not reported.

Both of these studies suggest a need for further examination of GRF variables in short-leg walkers. Zhang et al. (2006) also suggested that an insert on the shoe side may help to decrease the differences between normal gait patterns and short-leg walker gait patterns due to the decrease in heel height differences between the short-leg walker and shoe side. Reduction of some differences may result in fewer adverse effects associated with wearing a short-leg walker for an extended amount of time.

Limb length Discrepancy

A limb length discrepancy is created by the sole design of short-leg walkers. Zhang et al. (2006) noticed a significantly higher heel in two types of short-leg walkers when compared to normal shoes. This introduces an artificial limb length discrepancy. Limb length discrepancy may result in the initiation of compensatory mechanisms and produce adverse effects due to an altered gait pattern. Common compensatory techniques during walking include pelvic tilt, flexion of the hip and knee on the long side, while accommodating on the short side via ankle plantarflexion (Walsh et al., 2000).

Schuit et al. (1989) examined GRFs in subjects with structural limb length discrepancies and after the application of a heel lift to eliminate or reduce the structural limb length discrepancy. Eighteen subjects with a structural limb length discrepancy between 4.8 and 22.2 mm participated in this study. GRF data was collected prior to and after the application of a heel lift while each subject's self-selected walking speed was maintained. The heel lift was customized to produce level iliac crest height when limb length discrepancy was less than 12.7 mm. Level iliac crest height was not achieved in the remaining subjects (four); however limb length discrepancy was reduced. Heel lifts were fitted and each subject wore the heel lift for 21 days prior to testing to become accustomed to it.

Prior to the application of the heel lift, the difference of the maximum vertical GRF between the short and long limb was small (Schuit et al., 1989). After the application of the heel lift, the maximum vertical GRF difference was greater between the short and long limb, however the difference was not statistically significant. The application of the heel lift did result in a significant increase in maximum vertical GRFs in each leg when compared to GRF prior to the heel lift. The authors suggested that this difference may be related to the material used to make the heel lifts, as it was rigid (Schuit et al., 1989). The similar GRFs before the heel lift was introduced may be a result of the compensatory mechanisms that individuals have adopted in their gait patterns over time.

However, the artificial limb length discrepancy that is resulted from the application of a short-leg walker may have different effects than a true limb length discrepancy on GRFs. White et al. (2004) studied the impact of artificial and true limb

length discrepancy on GRF during treadmill walking using an instrumented treadmill that contained two force plates. For an artificial limb length discrepancy greater than one centimeter, the ground reaction force symmetry index was significantly different than no limb length discrepancy for peak weight acceptance, weight acceptance rate, push off, and push off rate (White et al., 2004). However, the true limb length discrepancy group (limb length discrepancy greater than one and less than three centimeters) only showed a significant increase in the weight acceptance force when compared to the no limb length discrepancy group. The authors speculated that the varying results between the two groups were due to long-term gait adaptations, which may be used by the true limb length discrepancy group. These compensatory mechanisms may also reduce asymmetric loading with time.

The majority of subjects showed greater loads and loading rates for the shorter limb, even though loading rate was only significantly greater in the artificial limb length discrepancy group. This suggests that the shorter limb is completing more work to move over the longer limb (White et al., 2004). These findings indicate that short-leg walkers need to be used with caution due to the greater loads and loading rates that may be placed on the shoe side. Depending on the length of time that a person is required to wear a short-leg walker, adverse effects may become prevalent due to the altered loading and gait patterns of the limbs.

Heel Height

Heel height has been studied extensively with regards to high-heeled shoes; however, there is very limited research as it is related to short-leg walkers. Earlier

research has looked at how varying heights of high-heeled shoes changed GRFs, rollover characteristics, and plantar pressure among females.

Yung-Hui and Wei-Hsien (2005) investigated the GRFs and plantar pressure data associated with increasing heel height and use of varying inserts. Ten females completed three trials in each heel height (flat, low, and high) and with each insert (heel cup, arch support, metatarsal pad, and total contact insert) and with shoes only. Each insert was customized for each subject. Walking speed was standardized across all subjects (1.3 m/s).

The authors observed an impact force imposed during load acceptance. The initial peak impact force occurred right after heel strike (Figure 1, see Appendix C). Increasing heel height was associated with the increased impact force. This impact force may have a ripple effect and travel up the lower extremity. This, in turn, may pose an increased risk of joint and musculoskeletal problems. A study of older heel strike runners found that older runners have an increased impact peak, which indicated that the shock absorbing capacity and the musculoskeletal system were compromised in older runners (Bus, 2003).

A significant decrease in the impact force for the heel cup and total contact insert at each heel height when compared to the shoe only condition was also found during this study (Yung-Hui and Wei-Hsien, 2005). A negative correlation was seen with respect to comfort ratings and impact force (Yung-Hui and Wei-Hsien, 2005). This may be relevant to the application and use of short-leg walkers as they also increase heel height. Extra care may need to be taken to ensure that sufficient cushion is applied to the insole of the short-leg walker to attenuate impact forces as well as increase comfort.

A study by Hansen and Childress (2004) examined the effect of heel height on rollover characteristics during level walking. Rollover shapes were found “by a transformation of the forward progression component of the center of pressure of the GRF under the foot from a laboratory coordinate system into the shank-based coordinate system for each sample between the times of heel contact and opposite heel contact” (Hansen and Childress, 2004). The rollover shapes represented the effective rocker geometries that the ankle and foot must conform to between heel contact and contralateral heel contact. Rollover characteristics are important when discussing the heel-to-forefoot difference found in short-leg walkers. However, there is limited information regarding rollover and short-leg walkers. Hansen and Childress (2004) determined that with increasing heel height, one adapts to maintain similar rollover characteristics. With high heels, the ankle joint goes into a more plantarflexed position to maintain rollover characteristics. This adjustment was found at the ankle (Hansen and Childress, 2004); however, in a short-leg walker, the ankle is stabilized, so GRFs and gait patterns may be adversely affected.

Corrigan et al. (1993) and Mandato and Nester (1999) examined forefoot plantar pressure with increased heel height. Corrigan et al. (1993) measured plantar pressure by using the Musgrave footprint pedobargraph while Mandato and Nester (1999) used an insole plantar pressure system.

Changes in heel height did not effect the total load of the forefoot (Corrigan et al., 1993), however, it did create a decreased contact area of the forefoot. This creates a significant increase in forefoot pressure in a raised heel condition due to the decreased contact area (Corrigan et al., 1993; Mandato and Nester, 1999). Both studies also found

that heel height shifts pressure to the medial forefoot during walking even though the methods used to measure forefoot pressure differed between the studies. Heel and forefoot height of short-leg walkers may need to be considered as a walking boot is prescribed to a patient. Depending on where an injury or ulcer occurs, this may translate into different types of walkers being better suited to heal a particular injury.

Kinematic and Kinetic Variables

Kinematic and kinetic analysis of short-leg walkers has been very limited. To date, two studies have addressed the three dimensional (3D) kinematics and kinetics of walking with a short-leg walker. Pollo et al. (1999) compared four short-leg walkers, a synthetic walking cast and normal shoes. Zhang et al. (2006) examined two short-leg walkers and normal shoes.

Pollo et al. (1999) concluded that short-leg walkers allowed subjects to better simulate normal walking than the synthetic walking cast. When using normal shoes as a baseline, the synthetic cast resulted in a significant reduction in gait velocity and cadence (Pollo et al., 1999). While all short-leg walkers outperformed the synthetic cast, the Bledsoe Boot performed the best with no significant differences in any of the kinematic or kinetic variables. The remaining three short-leg walkers had a significant difference in hip external moments in the frontal plane, which may contribute to adverse effects on the articular surfaces of the hip. The Cam Walker and the Royce Equalizer showed increased external flexion moments about the knee demanding greater effort of the knee extensors, which may result in adverse effects on the joints of the knee.

Pollo et al. (1999) attributed these differences to the varying sole design of the short-leg walkers. The short-leg walkers varied in heel height, sole rigidity, sole width,

and heel-to-forefoot height ratio (Pollo et al., 1999). The Bledsoe Boot had a soft sole and the lowest heel height, which may have enabled it to more closely simulate normal gait patterns. However, kinematic and kinetic data for all short-leg walkers showed fewer adverse effects on gait patterns than the synthetic walking cast (Pollo et al., 1999).

Zhang et al. (2006) examined the kinematics, kinetics, and ground reaction forces of two short-leg walkers compared to a normal shoe condition in eleven subjects. The Gait Walker showed a significantly greater maximum knee flexion angle when compared to the shoe condition. However, this was the only significant difference found for average peak and range of motion variables in the sagittal plane between walkers and shoe (Zhang et al., 2006). In the frontal plane, both short-leg walkers showed a significantly smaller hip abduction ROM when compared to the shoe condition. Joint kinetics revealed more significant results. A significantly greater peak plantarflexor internal moment and peak knee extensor internal moment were found for both short-leg walkers when compared to the shoe. Peak knee abduction internal moments were smaller in both short-leg walkers with the Equalizer being significantly smaller than the Gait Walker as well.

Results from Zhang et al. (2006) coincide with findings from Pollo et al. (1999) with few differences in kinematics in the sagittal plane. Zhang et al. (2006) did find kinematic differences in the frontal plane; however, the data suggest that the short-leg walkers restrict movement at the ankle joint. Pollo et al. (1999) did not track the ankle in their study. The smaller peak knee abduction moments that were found in Pollo et al. (1999) and Zhang et al. (2006) may be related to the application of the walkers as the knee abductors do not need to restrain adduction (Zhang et al., 2006). Greater knee

extensor moments were also seen in both Pollo et al. (1999) and Zhang et al. (2006). This may be related to the added weight of the short-leg walker or the increased heel height. Pollo et al. (1999) did not find any significant differences in kinematic and kinetic variables when looking at the Bledsoe Boot compared to shoe, which had the lowest heel height.

A walker that is better able to simulate normal walking with regard to kinematic and kinetic variables may be linked to similar ground reaction force in the walker and in normal shoes. This would be especially important as people transition from walking with a short-leg walker to walking without it.

CHAPTER III

METHODS

The purposes of this study were to investigate how heel height differences in the walker and shoe side may affect ground reaction forces (GRFs) when wearing a short-leg walker and the effects of heel height modification in the walker and/or shoe side on GRFs in walking. This chapter describes the procedures used in this study and will include the following sections: participants, instrumentation, testing procedures, walker modifications, and data and statistical analysis.

Participants

Ten healthy adults (age: 22.6 ± 1.68 years, height: $1.72 \pm .07$ m, mass: 72.55 ± 12.16 kg) from the University of Tennessee, Knoxville and the surrounding area were recruited to participate in this study. The participants consisted of four males and six females, free from injury and with a limb length discrepancy of less than one centimeter. All participants were screened prior to testing to ensure that they met the inclusion criteria and were willing to fully participate in the study. All participants were advised of the purpose and procedures of the study and signed an informed consent form prior to testing. The informed consent form was approved by the Institutional Review Board at the University of Tennessee, Knoxville.

Instrumentation

Anthropometric Measures: The mass and height of participants were measured using a calibrated physician's scale. In addition to height and weight, limb length was

measured while subjects were in a supine position, from the anterior superior iliac spine to the medial malleolus on both the right and left limbs.

Force Measurement System: Ground reaction force (GRF) data were collected using two force platforms (1200 Hz, AMTI Watertown, MA). The force platforms were staggered to obtain heel-strike and toe-off for left and right limbs. Electrical signals were amplified through two mini amplifiers (MSA-6, AMTI Watertown, MA). Data were sampled via Vicon datastation (120 Hz, Vicon, Oxford, UK).

Walking Speed: A pair of photocells (63501 IR, Lafayette Instrument Inc., IN) were centered around the force platforms and were connected to a multifunction timer (54035A, Lafayette Instrument Inc., IN) to monitor walking velocity.

Short-leg Walkers and Modifications

Two short-leg walkers were used in this study: Gait Walker (DeRoyal Industries, Inc., Powell, TN) and Equalizer (Royce Medical Co., Camarillo, CA) (Figure 2).

Walkers were worn on the right side with a lab shoe (Noveto, Adidas) worn on the left.

Walkers were always worn on the right due the numerous insoles that had to be created.

The padding for the walkers was altered slightly by cutting small pieces to expose the heel and forefoot regions for direct marker placement onto the foot. Small slits were cut one inch from the top of both walkers on the lateral arm to allow the arm of the plantar pressure insole sensor to be inserted into the cuff of the plantar pressure system during data collection. Medial arm and Velcro straps of the walkers were not altered.

Modifications did not decrease the overall integrity or performance of the walkers.

The heel and forefoot heights for lab shoes and walkers were measured using an Anthropometer (Model 01290, Lafayette Instrument Co., IN). Height measurements

were taken at the approximate location of the third metatarsal head on the insole for the forefoot and the middle heel region for the heel height.

A variable speed test stand and digital controller (Com Ten Industries 95 Series, Pinellas Park, FL) was used to measure foam deflection. The machine speed and strain gauge was calibrated prior to testing. Insole material samples were taken from the heel region for the Gait Walker and Equalizer. Samples were then trimmed into a 1-inch diameter circle for deflection testing. Insole material from the Equalizer was doubled to mimic thickness of Gait Walker material. Materials were tested at a peak force of 150 lbs. The average deformation obtained through the tests was included in the making of inserts for the Gait Walker to maintain a desired heel-forefoot height ratio.

The targeted heel-forefoot height ratio has been proposed from a previous study (Zhang et al., 2006). The heel-forefoot height ratio for Equalizer was 1.49 and was linked to a smoother transition from heel-strike to toe-off. The higher ratio allows progression of the center of mass, which is needed due to the restricted ankle dorsi-/plantarflexion (Zhang et al., 2006). This may facilitate walking better than the ratio seen in the Gait Walker (1.16). The ratio for the Equalizer walkers was approximated as 1.50. Therefore, the heel inserts were made for the Gait Walker to mimic the targeted ratio.

To make the heel inserts for the Gait Walker, three pieces of coring foam were cut, glued, and ground to match the contour of the heel. The height of the heel inserts was tapered down to 60% of the length of the foot. Heel inserts were attached to the walker's sole with double-sided tape during testing sessions and further secured to the walker due to application of Velcro straps on the walker.

Shoe inserts were also made to eliminate the artificial limb length discrepancy that is created with the application of the short-leg walker between the shoe and walker sides during walker testing conditions. Each insert was individually fabricated to match the respective heel heights of both walkers, with a foam piece ground down and then glued underneath an off-shelf shoe insert (Prostep, Talar Made Orthotics Ltd., UK).

Experimental Procedures

The protocol included one testing session conducted in the Biomechanics/Sports Medicine Lab, the University of Tennessee. Height and weight measurements were taken. Limb length was measured and recorded while the subject was in a supine position. If the subject met the inclusion criteria (free from injury and limb length difference < 1 cm), they continued with the testing session. During the actual testing portion of the session, walkers were worn on the right side with a lab shoe (Noveto, Adidas) worn on the left. Each subject performed five level walking trials in each of six randomized conditions: lab shoes (Shoe), Gait Walker (GW), Gait Walker with heel insert on shoe side (GWHI), Gait Walker modified to match Equalizer heel-to-forefoot height ratio with insert on walker side (GWM), Equalizer walker (EW), and Equalizer walker with heel insert on shoe side (EWHI). A walker condition (GW or EW) was randomly selected and was always performed first in order to obtain the subject's self-selected walking velocity.

The Shoe condition was performed in a pair of the lab shoes. The Gait Walker condition was performed in the Gait Walker and lab shoe. Gait Walker with heel insert was performed in the Gait Walker and the lab shoe that contained the altered Prostep insert to account for the difference in heel height between walker and shoe. The Gait

Walker modified was performed in the Gait Walker with heel insert on walker side and shoe with altered Prostep insert. This condition took into account heel height differences between walker and shoe and ratio of heel and forefoot height. The Equalizer walker condition was performed in the Equalizer and shoe on left side. The Equalizer with heel insert took heel height difference between walker and shoe into account and was performed with the Equalizer and shoe with altered Prostep insert.

Each subject was then fitted with one of the walkers, depending on randomization. The data collection system was calibrated prior to each testing session. Practice trials were performed to allow the subject to get accustomed to the walker and to ensure proper foot placement on the force platforms. Three trials of walking were used to collect the walking velocity. The average velocity was calculated and used to monitor the walking velocity during actual testing (average velocity $\pm 5\%$). If the velocity fell outside of the acceptable 5% range of the mean walking velocity, the trial was discarded and recollected. GRF data were collected for both the left and right limbs.

Data and Statistical Analysis

GRF variables were inspected and processed using a Visual3D software suite (C-Motion, Inc., MD). Ground reaction force data were smoothed at a cutoff frequency of 50 Hz using a 4th order zero-lag lower-pass Butterworth filter, and were normalized to body weight (BW). Maxima and minima were determined using a customized computer program (MS VisualBasic 6.0) from the output from Visual3D. The variables of interest included the initial peak GRF (F1), peak vertical GRF associated with load acceptance (F2), peak vertical GRF associated with push off (F3), GRF during midstance (Fmin),

peak anteroposterior braking GRF (Fb), peak anteroposterior propulsive GRF (Fp), time to F2 (T2) and time to F3 (T3) (Figure 3).

A 2×6 (side $\times$ condition) repeated measures analysis of variance (ANOVA) was used to evaluate selected variables, except F1, with an alpha level of 0.05 (SPSS 15.0, SPSS Inc., Chicago, IL). Post hoc comparisons were further conducted on significant variables by using a Bonferroni adjustment for multiple comparisons.

CHAPTER IV

GROUND REACTION FORCE CHARACTERISTICS ASSOCIATED WITH MODIFIED SHORT-LEG WALKERS

1. Introduction

Lower leg immobilization is necessary for the treatment of numerous injuries: severe ankle sprains, ankle and foot fractures, post surgical stabilization, and in the treatment of neuropathic foot ulcers (Crincoli and Trepman, 2001; Pollo et al., 1999; Zhang et al., 2006). In the past, synthetic total contact casts were the primary method used to immobilize the lower leg. It has become a norm to use short-leg walkers instead in these treatments. Short-leg walkers provide multiple benefits over total contact casts, which include decreased cost, ease of removal for cleaning or exercises, and recent studies have shown that they may produce fewer adverse effects on gait patterns and ankle musculature than a total contact cast (Pollo et al., 1999; Neumann et al., 1989).

Because short-leg walkers are being prescribed more recently, ankle and foot position in the short-leg walker needs to be considered in the treatment of a particular injury. It was found that alterations in the ankle position changed the plantar pressure for different areas under the foot (Baumhauer et al., 1997; Pollo et al., 2003), which is relevant as short-leg walkers are often used in the treatment of neuropathic foot ulcers (Crenshaw et al., 2004). By placing the ankle in a plantarflexed position, there are decreases in forefoot pressure and increases in hindfoot pressure (Crenshaw et al., 2004). When the ankle is placed in a more dorsiflexed position, forefoot pressure increases and hindfoot pressure decreases (Crenshaw et al., 2004). This is relevant as the location of

the ulcers varies among patients. Short-leg walkers have been shown to decrease plantar pressures (Baumhauer et al., 1997; Pollo et al., 2003) but the ankle position may also need to be considered when treating foot ulcers. While many studies have focused on plantar pressure characteristics, which are important, few studies have devoted to understanding characteristics of ground reaction forces (GRF) while wearing a walker. GRFs also play an important role when considering treatment for different injuries.

With the application of a short-leg walker, an artificial limb length discrepancy is imposed. Limb length discrepancy has been associated with asymmetrical loading during gait, which can lead adverse effects on the body (White et al., 2004). However, there is still debate regarding the similarities between true limb length discrepancy and artificial limb length discrepancy as well as which limb is receiving more of the load (White et al., 2004). Zhang and his colleagues (2006) suggested that the imposed artificial limb length discrepancy created by a short-leg walker may affect gait patterns, especially ground reaction forces. The duration of short-leg walker use may reach up to six months (Zhang et al., 2006), which may further exacerbate adverse effects on gait patterns. Research on biomechanical gait patterns in short-leg walkers has been very limited. Pollo et al. (1999) found that short-leg walkers produced fewer adverse effects during gait than a total contact cast. Zhang et al. (2006) found that the peak ground reaction forces associated with normal walking were not altered with the application of a short-leg walker. However, a small initial peak in ground reaction force was observed during early stance phase that was absent in normal walking. An elevated midstance GRF during walking was found for the Gait Walker compared to normal walking in shoes (Zhang et al., 2006). It was suggested that different ratios of the heel-to-forefoot height which were seen in the

two walkers allowed the Equalizer to simulate walking better than the Gait Walker (Zhang et al., 2006). To the author's knowledge, no studies have investigated the effects of the artificial limb length discrepancy introduced with the use of a short-leg walker on GRFs in gait. Further research is warranted in this area to obtain a better understanding of the changes in GRFs when using a short-leg walker. In particular, research regarding how to decrease any adverse effects that may be occurring by use of inserts to modify heel-to-forefoot height ratios and limb length discrepancies. Therefore, the purposes of this study were to investigate how heel height differences in the walker and shoe side may affect GRFs when wearing a short-leg walker and to determine the effects of heel height modification in walker and/or shoe side on GRFs in walking.

2. Methods

2.1. Participants

Ten participants (age: 22.6 ± 1.68 years, height: $1.72 \pm .07$ m, mass: 72.55 ± 12.16 kg) from the University of Tennessee, Knoxville, and the surrounding area participated in this study. The participants consisted of four males and six females, were free from injury and had a limb length discrepancy less than one centimeter. All participants were screened prior to testing to ensure that they met the inclusion criteria and signed an informed consent form approved by the University of Tennessee, Knoxville's Institutional Review Board.

2.2. Instrumentation

The limb length was measured while subjects were in a supine position from the anterior superior iliac spine to the medial malleolus on both the right and left limbs.

Ground reaction force (GRF) data were collected using two force platforms (1200 Hz, AMTI Watertown, MA, USA). A pair of photocells (63501 IR, Lafayette Instrument Inc., IN, USA) were centered around the force platforms and were connected to a multifunction timer (54035A, Lafayette Instrument Inc., IN, USA) to monitor walking velocity.

2.3. Short-leg Walkers and Modifications

Two short-leg walkers were used in this study: Gait Walker (DeRoyal Industries, Inc., Powell, TN, USA) and Equalizer (Royce Medical Co., Camarillo, CA, USA).

Walkers were always worn on the right side with a lab shoe (Noveto, Adidas) worn on the left. Padding and small slits were cut from the walkers to allow access to the foot and to allow access to a plantar pressure sensor arm. Medial arm and Velcro straps of the walkers were not altered.

The heel and forefoot heights for lab shoes and walkers were measured using an Anthropometer (Model 01290, Lafayette Instrument Co., IN, USA). Height measurements were taken at the approximate location of the third metatarsal head on the insole for the forefoot and the middle heel region for the heel height. These measurements were used in the creation of inserts to modify the heel-to-forefoot height ratio.

Insole material samples in the walkers were taken from the heel region for the Gait Walker and Equalizer. Deformation testing was completed (Com Ten Industries 95 Series, Pinellas Park, FL, USA) and the average deformation obtained through the tests was used in the fabrication of inserts for the Gait Walker to achieve a desired heel-to-forefoot height ratio. The desired heel-to-forefoot ratio has been proposed from a

previous study (Zhang et al., 2006). The heel-to-forefoot height ratio for Equalizer was 1.49 and was linked to a smoother transition from heel-strike to toe-off. Therefore, the heel inserts were made for the Gait Walker to mimic the targeted ratio of 1.50 as was estimated for the Equalizer's heel-to-forefoot height ratio. To create the heel insert for the Gait Walker, three pieces of coring foam were cut, glued, and ground to match the contour of the heel. The height of the heel inserts was tapered down to 60% of the length of the foot. Heel inserts were attached to the walkers' sole with double-sided tape during the testing sessions and further secured to the walker due to application of Velcro straps on the walker.

Shoe inserts were also made to eliminate the artificial limb length discrepancy that is created with the application of the short-leg walker between the shoe and walker sides during walker testing conditions. Each insert was individually fabricated to match the respective heel heights of both walkers, with a foam piece ground down and then glued underneath an off-shelf shoe insert (Prostep, Talar Made Orthotics Ltd., UK).

2.4. Experimental Protocol

In the study, all participants performed five level walking trials in each of six randomized conditions: lab shoes (Shoe), Gait Walker (GW), Gait Walker with heel insert on shoe side (GWHI), Gait Walker modified with insert on walker side (GWM), Equalizer walker (EW), and Equalizer walker with heel insert on shoe side (EWHI). A walker condition (GW or EW) was randomly selected and was always performed first in order to obtain the subject's self-selected walking velocity.

Practice trials were performed to allow the subject to become accustomed to the walker and to ensure proper foot placement on the force platforms. Three trials of

walking were used to collect the preferred walking velocity. The average velocity was calculated and used to monitor the walking velocity during actual testing. If the velocity fell outside of the acceptable 5% range of the mean walking velocity, the trial was discarded and recollected. Ground reaction force data were collected for both the right and left limbs.

2.5. Data Analysis

GRF variables were inspected and processed using a Visual3D software suite (C-Motion, Inc., MD, USA). Ground reaction force data were smoothed at a cutoff frequency of 50 Hz using a 4th order zero-lag lower-pass Butterworth filter, and were normalized to body weight (BW). Maxima and minima were determined using a customized computer program (MS VisualBasic 6.0) from the output from Visual3D. The variables of interest included the initial peak vertical GRF (F1), peak vertical GRF associated with load acceptance (F2), peak vertical GRF associated with push off (F3), GRF during midstance (Fmin), peak anteroposterior braking GRF (Fb), peak anteroposterior propulsive GRF (Fp), time to F2 (T2) and time to F3 (T3).

A 2×6 (side $\times$ condition) repeated measures analysis of variance (ANOVA) was used to evaluate the selected variables, except F1, with an alpha level of 0.05 (SPSS 15.0, SPSS Inc., Chicago, IL, USA). Post hoc comparisons were further conducted on significant variables by using a Bonferroni adjustment for multiple comparisons.

3. Results

The participants in this study performed the walking trials at a mean velocity of 0.93 m/s with a standard deviation of 0.12 m/s. The characteristics of the participants can be found in Table 1 (Appendix B).

The vertical and anteroposterior GRFs exhibited an initial peak (F1) prior to the normal peaks associated with walking for most participants (Figure 3, Appendix C). A significant interaction was present. The statistical results showed that the vertical GRF associated with loading was significantly higher for the shoe side than the walker side during the shoe condition ($P = 0.000$) (Table 2). There were no significant differences seen in any of the walker conditions for F2 or F3 ($P = 0.084$ and $P = 0.094$, respectively). The minimum vertical GRF also showed multiple significant differences. On the left side, the shoe condition was significantly lower than the Gait Walker (GW), Gait Walker with heel insert (GWHI), Gait Walker modified (GWM), and the Equalizer Walker with heel insert (EWHI) (Table 2, Figure 4). There was also a significant difference for Fmin between the left and right sides for shoe, GWHI, and Equalizer Walker (EW) for the minimum vertical GRF (Table 2, Figure 4). Fmin was significantly higher on the right side compared to the left for the shoe and EW conditions. For GWHI, Fmin was significantly higher on the left side when compared to the right side.

The time to F2 (T2) and F3 (T3) in the vertical GRF were fairly similar. There were no significant differences for the time to F2 ($P = 0.223$) (Table 3). However, T3 for EW was significantly greater than the shoe condition on the left side. Also, T3 for EW for the left side was significantly greater than the right.

For the anteroposterior GRF, there was a significant main effect of side and condition for the peak braking GRF (Fb). Post hoc comparisons revealed that on the left side, shoe was significantly greater than all other conditions for Fb (Table 4, Figure 5). Also, GW and EWHI were significantly greater for Fb than EW on the left side. On the right side, shoe was significantly greater for Fb compared to all other conditions. EWHI was also significantly greater than EW for Fb on the right side (Table 4, Figure 5).

The propulsive peak (Fp) revealed significant differences as well in the anteroposterior GRF. On the right side, all conditions were significantly lower when compared to the shoe condition (Table 4, Figure 6). The left side was significantly higher for GW, GWHI, EW, and EWHI than the right side. The right side was significantly higher for the shoe condition when compared to the left (Table 4, Figure 6).

4. Discussion

The main purposes of the study were to investigate how heel height differences in the walker and shoe side may affect GRFs when wearing a short-leg walker and the effects of heel height modification in walker and/or shoe side on GRFs in walking. An initial peak was found in the vertical GRF in each of the walker conditions for most participants. This finding coincides with the findings of Zhang et al. (2006). For F2, there was a significant difference in the shoe condition between right and left sides, with the left side being higher than the right (Table 2). This may be related to the application of the walkers. The walkers were always worn on the right side in this study. As suggested by White et al. (2004), the shorter limb may have a greater load and loading response. The left side showed significantly higher loading response than the right.

However, during this study, the significant difference was seen in the shoe condition, which was unexpected as there was no limb length discrepancy. This may have occurred due to the method of randomization that was used. A walker condition was always completed first. Therefore, when the subject performed the shoe trial they may have retained some of the gait characteristics that were acquired in the walker conditions. Subjects adjusted their load response when wearing a walker due to the added weight so that it was not significantly different from the shoe condition. However, in doing so when they returned to the shoe condition, F2 was then significantly lower on the right side compared to the left possibly due to the missing weight of the walker. We attempted to control for this by allowing each participant time to become accustomed to each condition. One subject also had an initial vertical GRF peak in the shoe condition as well. Once again, this may have resulted from the effects of wearing a short-leg walker first. No significant differences were seen in any of the walker conditions for the peaks associated with loading response and push-off (Table 2). These results are similar to the findings in the peak GRFs from the previous study (Zhang et al., 2006). The lack of difference in the peak vertical GRF may be related to the need to minimize peak GRF in gait when wearing a walker to promote healing (Zhang et al., 2006).

When examining the minimum vertical GRF that is associated with midstance, the results of this study vary from what was observed by Zhang et al. (2006). This study found no significant differences between any of the conditions and the shoe condition on the right side. However, on the left side the significant differences were found. The GW, GWHI, GWM, and EWHI exhibited a higher minimum GRF when compared to the shoe condition. Zhang et al. (2006) observed that the Gait Walker produced an elevated

minimum vertical GRF when compared to shoe on the walker (right) side. This study found no significant differences in the minimum GRF on the right side compared to the shoe condition. It was suggested that this elevated minimum may be related to the design of the sole of the walkers (Zhang et al., 2006). During the GWM condition, the heel-to-forefoot height ratio for the Equalizer was replicated with the use of an insert in the walker. This insert achieved the same heel-to-forefoot ratio that was found in the Equalizer walker; however, it did not introduce the hypothesized changes in the minimum GRF, as no significant differences were seen on the right side. The Equalizer walker was the only condition that was not significantly different from the shoe condition on the shoe (left) side. However, its large standard deviation may have clouded the results. It is interesting to note that the elevated minimum was not seen on the walker (right) side, but on the shoe (left) side. An elevated F_{min} may be expected in GW, as a limb length discrepancy was imposed by the walker. White et al. (2004) found that the shorter limb sustained a greater load (F_2) and greater push off (F_3) than the longer limb in their study. If F_2 and F_3 is greater in the shorter limb, it is reasonable to think that F_{min} may have also been elevated, to enable to shorter limb to vault over the longer limb (White et al., 2004). However, we did not expect to see an elevated F_{min} in GWHI, GWM, or EWHI as the limb length discrepancy was eliminated with the use of a heel insert. The elevated F_{min} on the left side seen in all conditions but EW when compared to shoe may have been related to the uncomfortable nature of wearing a walker and restricted ankle motion. The practice period may need to be extended to allow the participant to become better accustomed to the walker. The higher F_{min} on the left side

may be due to adaptation to the raised right heel on the walker side. This adaptation may be revealed through the joint kinematics and kinetics.

There were also significant differences in F_{min} between the right and left sides for the shoe, Gait Walker with heel insert and the Equalizer walker. During the shoe and EW condition the minimum was elevated on the right (walker) side when compared to the left (shoe). However, during the Gait Walker with heel insert condition, the minimum vertical GRF was lower on the right side when compared to the same condition on the left side. White et al. (2004) found that the shorter limb sustained a greater load than the longer limb in their study. Although we did not observe significant differences in peak vertical GRFs between the two sides in the condition of the Gait Walker where a limb length discrepancy was introduced by wearing the walker, this may still be relevant as it relates to F_{min} . Because the shorter limb sustains more of the load, it may also have an elevated minimum compared to the longer limb, which is seen in the results as GWHI on the left side had a higher F_{min} than on the right side. This is not what we expected to find. The heel insert in GWHI was placed on the left side to eliminate the limb length discrepancy that is imposed by the walker. We would have expected to see an elevated F_{min} on the left side during the GW and EW. The EW and shoe conditions showed a lower F_{min} on the left side compared to the right. The lower F_{min} on the left side for shoe may be related to gait characteristics that were retained from walker trials. The lower F_{min} on the left side for EW may be important as it relates to the elevated F_{min} on the right side. This may be important as it applies a constant load that is felt by the foot on the walker side during midstance. Typically, a walker is prescribed to patients who

sustain an injury to the lower extremity. It may be useful to have a more constant load applied to the foot in the walker during midstance (Zhang et al., 2006).

The peak braking ground reaction force (Fb) did not show a significant interaction between side and condition; however, the main effect of side was significant (Table 4, Figure 5). All walker conditions were significantly smaller than shoe for both the left and right sides. On the left side the decreased Fb may be related to the decreased propulsive force (Fp) that was seen in all walker conditions when compared to shoe on the right side. On the right side, the decrease Fb may occur due to the participant attempting to control the added weight of the walker and therefore creating a decreased braking force in the walker conditions compared to shoe. Muscles in the lower leg on the walker side may control the walker to limit excessive impact force as the walker strikes the ground, which would also minimize the peak braking force. This may also be a contributing factor to the decreased Fbs that are seen on the right side when compared to the left in shoe, GW, GWHI, and GWM. However, these differences were not seen in the vertical GRF. The GW and EWHI were both significantly greater than EW on the left side and the EWHI was also significantly greater than EW on the right side. These differences may be related to the sole design of the EW as suggested by Zhang et al. (2006). The greater heel-to-forefoot ratio may facilitate progression of the foot better (Zhang et al., 2006), especially when the shorter limb is vaulting over the longer limb. Once the limb length discrepancy was adjusted for in EWHI, the Fb was similar to those seen in the other walker conditions on both sides.

The propulsive force in the anteroposterior GRF was significantly lower on the right (walker) side compared to the left (shoe) for all conditions except for the Gait

Walker modified (Table 4, Figure 5). This may be related to the difficulty of rollover of the foot from heel strike to toe off in the walker condition. The modified Gait walker did not show a difference in the peak propulsive force even though the Equalizer Walker did show a significant difference. This is interesting, as the insert on the walker side in the modified Gait Walker seemed to facilitate the rollover due to the modified heel-to-forefoot height ratio that is seen in the Equalizer walker. It would be expected to see the same results in the Equalizer Walker. The decrease of propulsive force seen on the right side may also be related to the restriction of the ankle joint motion that the walkers provided. Moreover, on the right side, all conditions were significantly lower than the shoe, also indicating that the walkers provide restriction of the ankle, which reduces the propulsive force that can be applied by the foot.

Overall, the short-leg walkers imposed an initial peak (F1) prior to those associated with normal walking in the vertical GRF. Multiple differences were observed in Fb and Fp during the walker conditions and the inserts used to eliminate limb length discrepancy did not return GRFs to those seen in normal shoes.

5. Conclusions

The results showed that all walker conditions imposed a small initial peak prior to those associated with normal walking in the vertical GRF. The anteroposterior GRF also showed significant differences in the braking and propulsive forces during walker conditions. Modifications used to decrease limb length discrepancy created by the application of a walker did not return GRFs to those seen in normal shoes. It may be necessary to test these modifications after a period of adjustment (multiple days) as was

completed in the study regarding limb length discrepancy by Schuit et al. (1989). This may prove difficult, as most participants would be unwilling to wear an unnecessary walker for an extended period of time (days or weeks). It would also be valuable to study kinematic and kinetic variables and how inserts impact these variables. Even though there was not a consistent change in the GRF variables among the varying conditions with inserts, the kinematic and kinetic variables may provide a better understanding of what is occurring to the body when a walker is being used. The modifications may produce beneficial results that are only reflected in the joint kinematics and kinetics of walking with a short-leg walker. Future modifications to the short-leg walker also need to be considered. Attempting to make the short-leg walker more similar to a running shoe may decrease the differences that have been seen between the short-leg walkers and running shoes.

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APPENDICES

APPENDIX A

Physical Activity Readiness Questionnaire

Name: _____ Date(MM/DD/YY): ____/____/____

Please answer the following questions to the best of your knowledge (circle YES or NO).

1. **Yes** **No** Has your doctor ever said you had heart trouble or a heart murmur?
2. **Yes** **No** Do you ever suffer pains in your chest?
3. **Yes** **No** Do you ever feel faint or have spells of severe dizziness, passed out, palpitations or rapid heart beat?
4. **Yes** **No** Has the doctor ever told you that your blood pressure was too high? (systolic $\geq$ 160 mm Hg or diastolic $\geq$ 90 mm Hg on at least 2 separate occasions)
5. **Yes** **No** Do you smoke cigarettes?
6. **Yes** **No** Do you have any neuropathy as a result of diabetes?
7. **Yes** **No** Do you have a family history of coronary or other atherosclerotic disease in parents or siblings prior to age 55?
8. **Yes** **No** Has your serum cholesterol ever been elevated?
9. **Yes** **No** Is there any physical reason not mentioned here why you should not follow an activity program even if you wanted to?

Below please provide an explanation for any of the questions to which you answered YES.

Participant # : _____

Participant initials : _____

Demographic Questionnaire

Name _____ Date (MM/DD/YY): ____/____/____

Shoe Size (US) _____ Age (in years) _____

Gender: (check one) ☐ 1. Female ☐ 2. Male

Height: ____ Feet, ____ Inches or _____ cm

Weight: _____ lbs or _____ kg

Please Check One:

Do you use specialized insoles or foot orthotics? ☐ 0. NO ☐ 1. Yes

Do you have any injuries that may affect the way you walk or run:

☐ 0. NO ☐ 1. Yes

If YES, please describe the injury, and when it happened:

Have you injured your lower extremities in the last year:

☐ 0. NO ☐ 1. Yes

If YES, please describe the injury, and when it happened:

Participant #: _____

Participant initials: _____

Informed Consent Form

“A follow-up study on 3D biomechanics of short-leg walking boots”

Investigator: Songning Zhang, Ph.D.
Address: Biomechanics/Sports Medicine Lab
The University of Tennessee
1914 Andy Holt Avenue
Knoxville, TN 37996
Phone: (865) 974-2091

Introduction

You are invited to participate in a research study on walking characteristics in two short-leg walkers. The purpose of the study is to examine characteristics of three-dimensional kinematics, ground reaction forces, joint kinetics and muscle electrical activities of the lower extremities during walking in two walking boots designed for treatments of various injuries, including foot fractures and severe ankle sprain.

Testing Protocol

You should have had no history of major injuries to the lower extremity and be injury free at the time of testing. You will be asked to attend one biomechanical test session that will take approximately 1.5 to 2 hours to complete. At the beginning of the biomechanical test session, you will fill out one demographic questionnaire and a questionnaire about your physical activity readiness. Before the actual testing, your walking speed will first be determined wearing a shoe on the left side and a short-leg walker on the right side by averaging the speeds of three walking trials. During the testing, you will be asked to wear one of the two short-leg walkers with and without modifications, on the right foot and a lab shoe, with and without modifications on the left foot. During the actual testing, you will perform 5 level walking trials in each of six testing conditions with combinations of the above-mentioned boots (unmodified and modified) and the lab shoe. During the test, biomechanics instruments will be used to obtain measurements. Some of these instruments will be placed/fixed on your body. None of the instruments will impede your ability to engage in normal and effective motions during the test. If you have any further questions, interests or concerns about any instrumentation, you are free to ask at any time.

Potential Risks

Walking in the boots and shoe involved in this study will not require you to exert efforts that exceed your normal daily walking. A potential risk includes an ankle sprain from walking in an unbalanced fashion on an uneven terrain. Every effort will be made to reduce this risk through sufficient practice in the tested boots and shoe. The lab is equipped with a level walking surface with no intrusive objects in the testing area. All tests will be conducted and the equipment will be handled by the qualified research personnel in the Biomechanics/Sports Medicine Lab. The Biomechanics/Sports Medicine Lab has tested more than 600 subjects in many research projects related to dynamic movements over the past 10 years and none have been injured in any fashion

during the test sessions. You will be encouraged to warm up actively prior to the testing session so that you feel physically prepared to perform effectively and thus minimize any chance for injury. Should any injury occur during the course of testing, standard first aid procedures will be administered as necessary. At least one researcher with a basic knowledge of athletic training and/or first aid procedures will be present at each test session. In the event a physical injury is suffered as a result of participation in this study, the University of Tennessee will not automatically provide reimbursement for medical care or other compensation.

Benefits of Participation

Your benefits include assessment of your performance and biomechanics of walking and walking boot selection. You are welcome to make an appointment to review the data from your tests. In addition, if you wish to have a copy of the results of the study, please let me know.

Confidentiality

Your participation is entirely voluntary and your decision not to participate will involve no penalty or loss of benefits to which you are otherwise entitled. Your identity will be held in strict confidence through the use of a coded subject number during data collection, data analysis, and in all references made to the data, both during and after the study, and in the reporting of the results. Any information about your identity will remain confidential and will be disclosed only with your permission. The results will be disseminated in the form of presentations at conferences and publications in journals. The information sheet, consent form and video tape containing your identity information will be destroyed three years after the completion of the study. If you decide to withdraw from the study, your information sheet and consent form with your identity and injury history will be destroyed upon withdrawal of the study.

Contact Information

If you have any questions at any time about the study you may contact Dr. Songning Zhang. Questions about your rights as a participant can be addressed to Research Compliance Services in the Office of Research at (865) 974-3466.

Consent

By signing, I am indicating that I understand the potential risks and benefits of participation in this study and that I am agreeing to participate in this study.

Subject's Name:

Signature:

Date:

Investigator's Signature:

Date:

APPENDIX B

Table 1. Descriptive Characteristics

Subject	Age (years)	Height (meters)	Weight (kilograms)
1	23	1.71	75.45
2	26	1.70	71.82
3	22	1.83	93.18
4	21	1.70	58.64
5	23	1.77	66.36
6	18	1.70	64.55
7	23	1.63	53.18
8	23	1.57	59.09
9	21	1.80	100.00
10	26	1.83	81.82
Mean (SD)	22.6 (1.68)	1.72 (0.07)	72.41 (12.16)

Table 2. Means (Standard Deviations) of vertical GRF (BW)

Side	Condition	F1†	F2	Fmin	F3
L	Shoe	-	1.146 (0.09)*	0.823 (0.05)*	1.151 (0.08)
	GW	0.993 (0.12)	1.120 (0.09)	0.883 (0.05) ^a	1.153 (0.09)
	GWHI	1.001 (0.08)	1.127 (0.07)	0.886 (0.05)* ^a	1.129 (0.08)
	GWM	1.018 (0.11)	1.131 (0.10)	0.888 (0.05) ^a	1.145 (0.10)
	EW	0.944 (0.09)	1.125 (0.08)	0.644 (0.28)*	1.149 (0.08)
	EWHI	1.005 (0.15)	1.135 (0.07)	0.883 (0.05) ^a	1.140 (0.08)
R	Shoe	-	1.101 (0.08)	0.845 (0.05)	1.135 (0.08)
	GW	0.786 (0.21)	1.154 (0.08)	0.760 (0.27)	1.005 (0.36)
	GWHI	0.777 (0.19)	1.153 (0.07)	0.858 (0.06)	1.130 (0.08)
	GWM	0.760 (1.6)	1.122 (0.08)	0.861 (0.06)	1.101 (0.08)
	EW	0.738 (0.17)	1.107 (0.07)	0.878 (0.06)	1.113 (0.05)
	EWHI	0.740 (0.12)	1.123 (0.05)	0.868 (0.05)	1.136 (0.06)

Note: (†) – no statistics analyzed
 (*) - significantly different from the right side of the same condition.
 (^a) – significantly different from Shoe of the same side.
 (-) – no peak observed.

Table 3. Means (Standard Deviations) for Time (s) to peak vertical GRFs

Side	Condition	T2	T3
L	Shoe	0.183 (0.03)	0.555 (0.03)
	GW	0.343 (0.14)	0.562 (0.06)
	GWHI	0.272 (0.12)	0.761 (0.28)
	GWM	0.339 (0.15)	0.577 (0.05)
	EW	0.275 (0.10)	0.597 (0.05)* ^a
	EWHI	0.301 (0.14)	0.583 (0.04)
R	Shoe	0.239 (0.12)	0.567 (0.03)
	GW	0.301 (0.12)	0.517 (0.19)
	GWHI	0.261 (0.08)	0.555 (0.05)
	GWM	0.292 (0.09)	0.579 (0.06)
	EW	0.249 (0.07)	0.568 (0.04)
	EWHI	0.240 (0.07)	0.560 (0.04)

Note: (*) - significantly different from the right side of the same condition.
(^a) – significantly different from Shoe of the same side.

Table 4. Means (Standard Deviations) of anteroposterior GRF (BW)

Side	Condition	Fb	Fp
L	Shoe	-0.196 (0.04)*	0.171 (0.03)*
	GW	-0.153 (0.04)* ^{a b}	0.172 (0.03)*
	GWHI	-0.156 (0.04)* ^a	0.173 (0.03)*
	GWM	-0.149 (0.05)* ^a	0.166 (0.02)
	EW	-0.131 (0.04) ^a	0.183 (0.03)*
	EWHI	-0.159 (0.04) ^{a b}	0.180 (0.03)*
R	Shoe	-0.156 (0.04)	0.199 (0.03)
	GW	-0.128 (0.03) ^a	0.154 (0.04) ^a
	GWHI	-0.135 (0.04) ^a	0.141 (0.04) ^a
	GWM	-0.120 (0.03) ^a	0.148 (0.03) ^a
	EW	-0.125 (0.03) ^a	0.130 (0.03) ^a
	EWHI	-0.145 (0.03) ^{a b}	0.131 (0.02) ^a

Note: (*) - significantly different from the right side of the same condition.
^(a) – significantly different from Shoe of the same side.
^(b) – significantly different from EW of the same side.

APPENDIX C

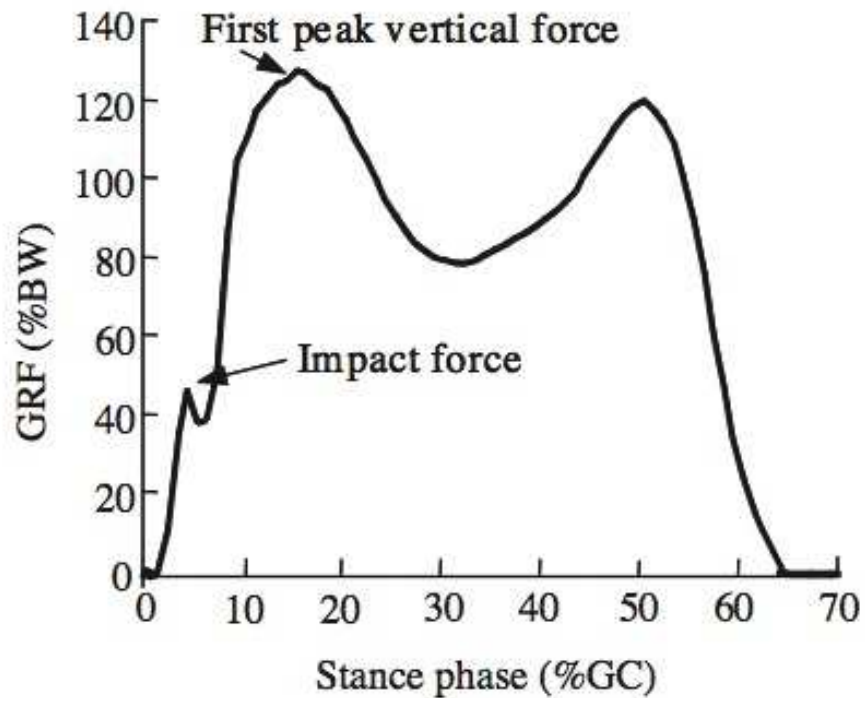


Figure 1. Vertical GRF from Yung-Hui and Wei-Hsien (2005).

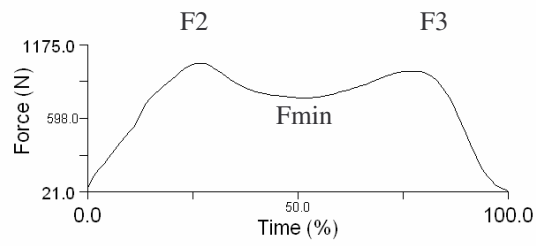


(A)

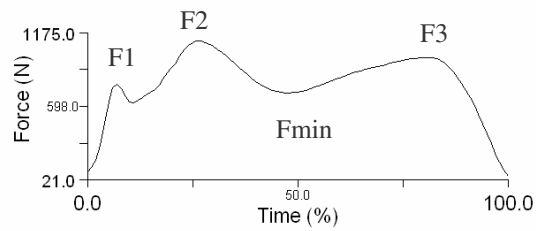


(B)

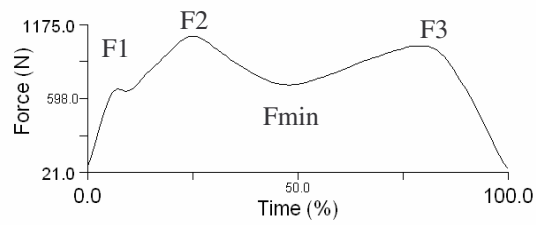
Figure 2. Gait Walker (A) and Equalizer Walker (B).



(A)



(B)



(C)

Figure 3. Representative vertical GRF curves in three different testing conditions: shoe (A), Gait Walker (B), and Equalizer (C).

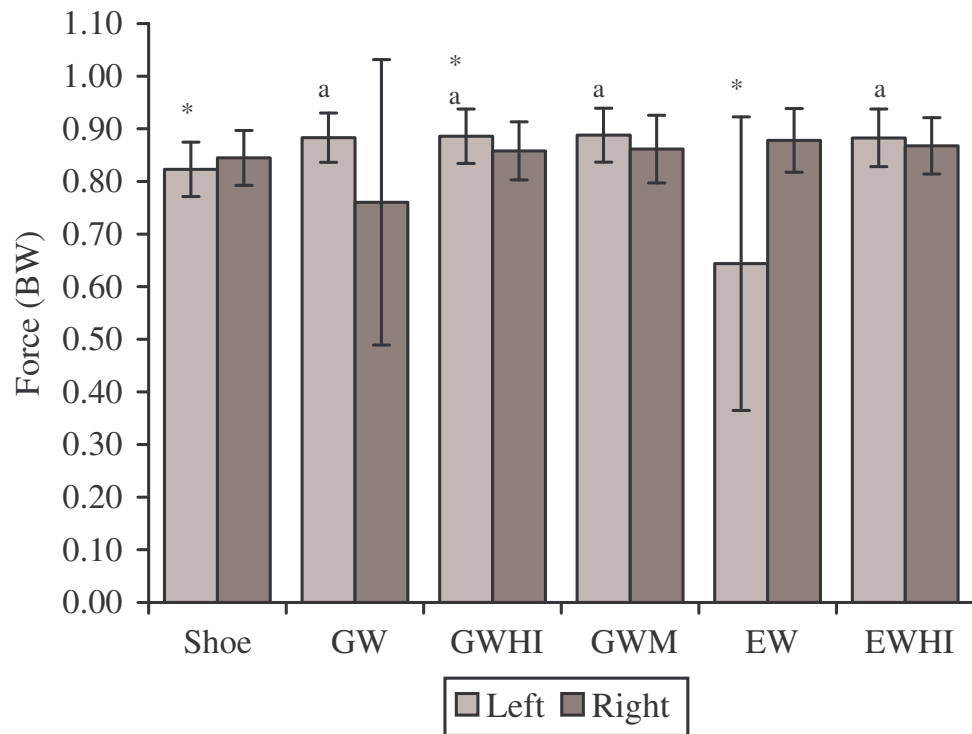


Figure 4. Means and standard deviations of the minimum vertical GRFs (Fmin) during midstance; (*) significantly different between the left and right side of the same condition and (a) significantly different from Shoe of the same side.

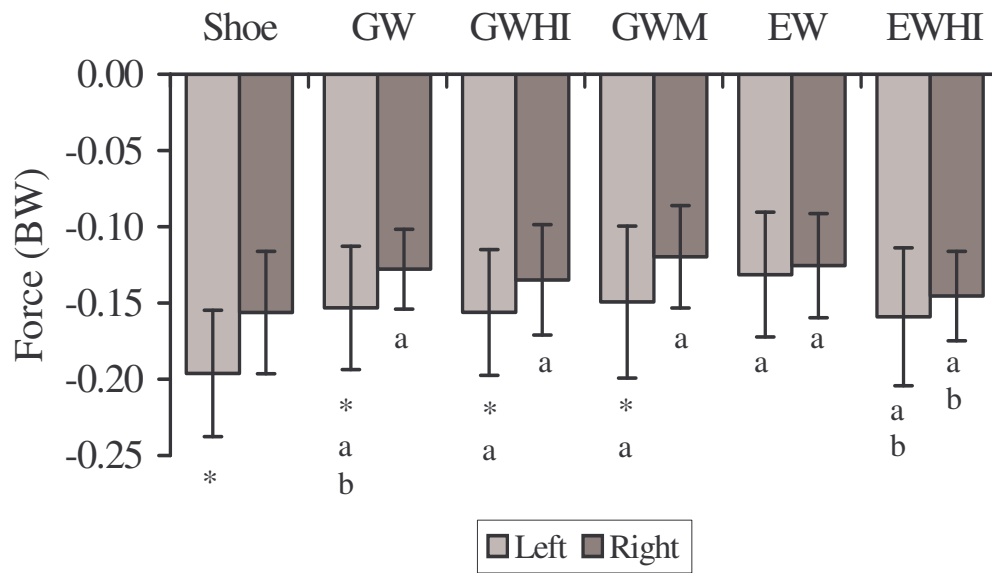


Figure 5. Means and standard deviations of the minimum anteroposterior GRFs (Fb); (*) significantly different from the right side of the same condition, (a) significantly different from shoe of the same side and (b) significantly different from EW of the same side.

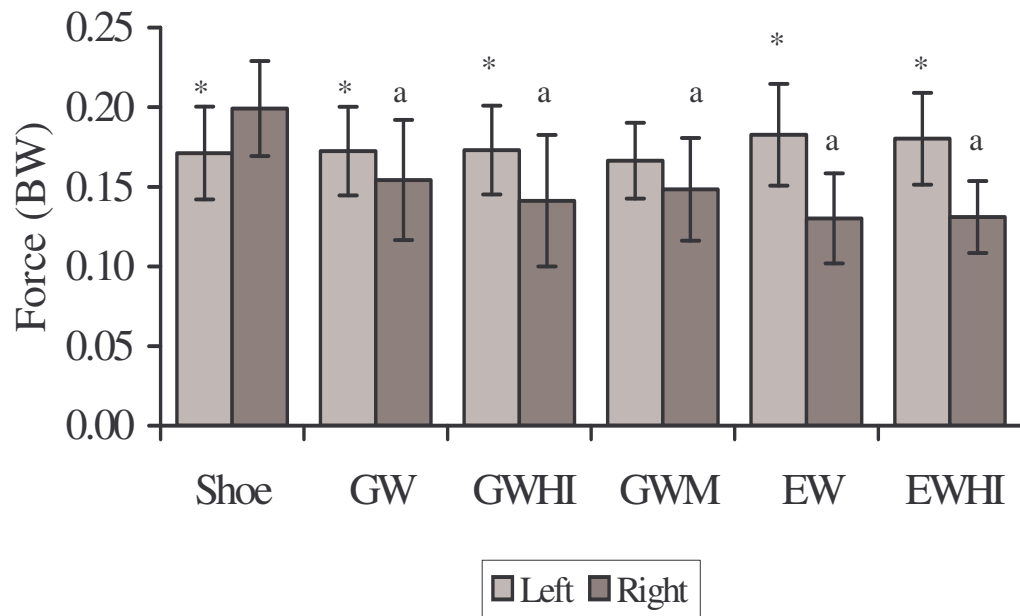


Figure 6. Means and standard deviations of the maximum anteroposterior GRFs (Fp); (*) significantly different between left and right side of the same condition and (a) significantly different from Shoe of the same side.

VITA

Maria Keefer was born in Columbus, OH to the parents of Loren and Pamela Keefer. She is the last of four daughters: Lara, Sara, and Amanda. She attended Highland East Elementary and continued to Highland High School in Sparta, Ohio. After graduation, she headed south to Miami University of Ohio where she was introduced to Exercise Science and Biomechanics. Maria completed an International Health Study Abroad Program with Dr Reginald Fennell, which was an exciting and challenging experience and pushed her into continuing her education. She obtained a Bachelors of Science degree from Miami University in May 2005 in Exercise Science. She accepted a graduate teaching assistantship at The University of Tennessee, Knoxville, in the Physical Education and Activities Program and in the Biomechanics/Sports Medicine Lab. Maria graduated with a Masters of Science degree in Exercise Science in May 2007. She is continuing her education with a Masters of Public Health at the University of Texas at Houston, TX.