American Orthotic and Prosthetic Association (AOPA) Center for Orthotics and Prosthetics Learning and Outcomes/Evidence-Based Practice (COPL)

Project Description – 12 Month Final Report Summary (July, 2011-August, 2012)

Project title:
Influence of the rocker profile in an orthosis-footwear combination to modulate neuromuscular behavior

Investigators:
Christopher Hovorka, MS, CPO, LPO, FAAOP, Young Hui Chang, PhD, Geza Kogler, PhD, CO, LO, (Research assistants: Simisola Oludare, Jaemin Sung, Tiffany Yan, Katie Eckert, Shannon Mullaney)

Georgia Tech project number: 40066F3

Introduction:
As the principal investigator and on behalf of the investigator team, we are grateful to the AOPA COPL for the funding of the investigation that enabled us to advance the project. Because the investigation employs a perturbation to subjects over a moderate duration (i.e., mechanical lower limb constraint for over one hour of walking), we discovered many challenges with the technology used to constraint subject's lower limbs and the substantial data array collected. Because of the extensive data array generated by each subject's participation in the extensive protocol, we continue our efforts to process and analyze the data.
In order to provide a representative overview of the successes and accomplishments of the project, we will focus on two lines of research focused on examining the roll over exhibited by subjects in response to constraint of movement and a footwear system.

Summary of Recognition/Accomplishments:
Portions of the discoveries from the current project will be presented at the American Orthotic and Prosthetic Association's Annual Assembly in Boston next month (September). A research poster entitled, "**Biomimetic rocker profile restores lower limb rollover when walking with constraint of ankle-foot motion**" will be delivered at the poster session by Simisola Oludare, a Georgia Tech undergraduate Biomedical Engineering Student who has served as a research assistant on the project.
Simisola has leveraged his work on the current line of AOPA COPL funded research and was awarded the Georgia Tech President's Undergraduate Research Award (PURA). This is a **prestigious research award** that provides paid salary for a semester of research to only 90 undergraduate students among thousands of students at the Institute. In addition, Simisola was the only student in the School of Applied Physiology to receive this award (which is a testament to the novelty of the research and its potential for clinical impact).

In addition, a podium presentation entitled, " **Rocker profile sole influences movement behavior**" will be presented by the project's principal investigator (Christopher Hovorka) at the Pedorthic Session.

Research Personnel and Laboratory Collaborations:

The project involved an array of students and extensive collaboration of resources from three laboratories (Hovorka – Neuromuscular Behaviors Lab, Chang – Comparative Neuromechanics Lab, Kogler – Clinical Biomechanics Lab)**.** In addition, undergraduate student volunteer research assistants (Jaemin Sung, Tiffany Yan) and a graduate student in the Master of Science in Prosthetics and Orthotics program (Shannon Mullaney) were added to the staff of the project since January 2012. The students collaborated with other research assistants (Simisola Oludare and Katie Eckert) and assisted the principal investigator (Christopher Hovorka) and Dr. Geza Kogler (co-investigator) in designing, creating and evaluating footwear systems and revising the computer coding (Matlab, Mathworks) for processing and analysis of the considerable data array generated by the instrumented walking protocols.

Overview of Lines of Research:

We extended our work in the current project from a previous line of research examining neuromuscular response to constraint of ankle motion of subjects while walking with a unilateral AFO-footwear combination (AFO-FC) (**Figure 1**). The same AFO-FC was utilized for the current project to examine the performance of the footwear combination in restoring roll over during stance phase of gait when the ankle and foot are constrained. In addition, a new footshell-footwear combination was designed, created and validated.

Figure 1. AFO-Footwear Combination and Footshell-Footwear Combination.
A custom AFO-footwear combination (AFO-FC) was designed, validated and fit to subject's right lower limb to constrain ankle motion as each subject walked at their self-selected comfortable speed. A custom footshell-footwear combination (FS-FC) was also designed, validated and fit to subject's left lower limb to serve as control. A rocker profile that emulated the normal (unconstrained) roll over shape is illustrated on the plantar aspect of the right AFO-FC and on the left FS-FC. The images illustrate the AFO-FC in the Plantarflexion Stop Dorsiflexion Stop (PSDS) constraint condition and the left FS-FC as the subject walked overground. In the actual protocol, subjects walked in a gait lab over a dual-belt treadmill with embedded force plates while fully instrumented (i.e., wearing safety harness and data collection instrumentation).

Preliminary Results: Rocker Profile Effectively Preserves Lower Limb Roll Over:
The roll over shape (ROS) provides a simple and discreet expression of the roll over performance of the ankle and foot complex over the entire stance phase of gait. To determine this, we calculated roll over shape radius of curvature in a shank-based coordinate system (described in the 6-month report). In the first six months of the investigation we evaluated the roll over shape of the footwear by examining a single subject walking with their ankle constrained by an AFO and wearing a footwear combination that consisted of a rocker profile attached to the plantar aspect of the right AFO. The subject used a commercially available extra depth footwear system on the left leg (Apis, El Monte, CA). Results from that study revealed a roll over radius (mean±standard deviation) of the right leg in the most constraining condition (i.e., plantarflexion stop, dorsiflexion stop) of **0.26±0.01**. When this value is compared to the normal unconstrained roll over radius (**0.30**) it provides evidence that the AFO-FC (when set in the most constraining ankle condition) produced a near normal roll over shape. **The results were encouraging because it suggested that the rocker profile restored roll over in spite of constraint of ankle and foot motion by the AFO.**

However, we were unsure if the shoe worn by subject on their unconstrained left lower limb may have confounded the results of the subject's walking behavior (and thus may perhaps have influenced the results of the rocker profile restoring roll over on the constrained right leg). To control for possible influence of the left shoe, we designed a pair of footshell-footwear combinations for the right and left legs to serve as a new control condition. In addition, the left footshell-footwear combination would be worn by subjects during all right ankle constraint conditions (i.e., when wearing the right AFO-FC). In addition, subjects would walk with left and right footshell-footwear combinations as a control. This new research design would thus minimize any variability in footwear systems between the right and left legs when subjects walked with and without ankle constraint of motion.

Revised Protocol and Results: Rocker Profile Effectively Preserves Lower Limb Roll Over:
For the revised protocol utilizing right AFO-FC and left FS-FC for ankle constraint conditions and bilateral FS-FC as control, we recruited five healthy subjects (4 males, 1 female, age: 34.66 yr, weight: 70.15 kg, height 171.46 cm, walking speed: 1.31 m/s) and collected kinematics and kinetics data as subjects walked in an instrumented gait lab on a dual-belt treadmill in five

randomized conditions (control and four constraint conditions). Control condition consisted of footshell-footwear combination – which involved no ankle constraint. The four ankle constraint conditions consisted of plantarflexion free dorsiflexion free, plantarflexion free dorsiflexion stop, plantarflexion stop dorsiflexion free, plantarflexion and dorsiflexion stop. Examination of the processed and analyzed data for roll over radius reveals subjects preserved roll over during gait when walking with an ankle foot orthosis-footwear combination on the constrained side (right) and no ankle constraint (unconstrained) on the left lower limb during all conditions during the first eight minutes (**Figure 2)**.

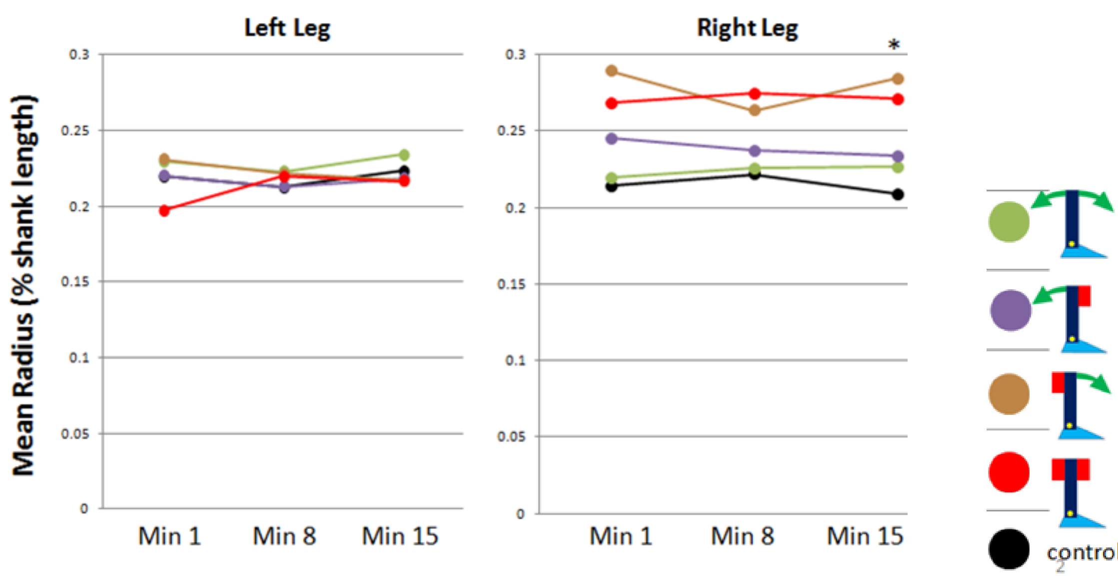

Figure 2a. Left Leg Roll Over Radius   Figure 2b. Right Leg Roll Over Radius

Figure 2. Left and Right Leg Roll Over Radius during Stance Phase of Gait
Figure 2a (left leg) and Figure 2b (right leg) roll over radius during 15 minutes of walking with right leg in five different conditions (black – control [consisting of footshell-footwear combination – no ankle constraint] and four ankle constraint conditions [green – plantarflexion free dorsiflexion free, purple – plantarflexion free dorsiflexion stop, brown – plantarflexion stop dorsiflexion free, red – plantarflexion and dorsiflexion stop]).

Statistical analysis for roll over radius of right lower limb during stance phase of walking revealed no difference in constraint conditions compared to control during minute 1 and 8 ($p>0.05$). During minute 15, there was a significant trend ($p=0.05$) for difference between plantarflexion stop dorsiflexion free (brown) and plantarflexion stop dorsifleixon stop (red) ankle constraint compared to control but not for plantarflexion free dorsifleixon stop (purple) or plantarflexion and dorsiflexion free (green). Roll over radius of left lower limb during stance phase of walking was no different in constraint conditions compared to control in minute 1, 8 and 15 ($p>0.05$).

We interpreted these results to indicate that the footwear designed with a rocker profile restored lower limb roll over even though the ankle and foot complex were constrained by the AFO. This was the case for all conditions for all minutes except for the plantarflexion stop conditions (brown and red in Figure 2 right leg graph) for the 15^{th} minute.
These results represent new knowledge regarding the performance of a footwear system designed with a rocker profile to emulate the unconstrained ankle-foot complex during stance phase of gait. This is because little information is currently available that characterizes the design and biomechanical performance of footwear systems intended to restore stance phase roll over.

Next Phase of Project – Determine New Rocker Profile Shapes:
The first line of research to examine the roll over produced by a designed footwear system with a rocker profile, established that the rocker profile emulated the "normal" roll over in spite of ankle-foot constraint of motion by an AFO. However, we had not established the rocker profile design that emulated the "slow" and "fast" roll over conditions. To accomplish this goal, we aimed to first characterize and quantify the biomechanics of the metatarsophalangeal (MTP) joints of the foot during unconstrained standing and walking. This is because the MTP joints play a significant role in influencing the performance of roll over shape during terminal stance phase of gait.

Quantifying Normal Function and Displacement of the Forefoot during Terminal Stance:
The next pages of the report present an extensive line of research in which we collaborated with the Clinical Biomechanics Lab (CBL) at Georgia Tech's School of Applied Physiology to better understand and quantify forefoot function during terminal stance phase of gait beyond the general expression of stance phase via the roll over shape. The CBL is operated by Geza Kogler, PhD, CO (who also serves as a co-investigator of the AOPA COPL grant). Dr. Kogler assigned one of his research staff (Shannon Mullaney) to address this line of research.

The line of research involved a pilot investigation in which gyroscopes (Inertial Measurement Unit VN 100, Vectornav Technologies) and force resistive sensors (Model FSR 402 0.5" Interlink Electronics) were used by subjects while standing and walking. The aim of the investigation was to quantify and characterize forefoot displacement at a level beyond that of the instrumented gait analysis laboratory in which the earlier lines of research examining the roll over performance of the footwear system as a rocker profile were conducted.

Kinematic Analysis of Terminal Stance Motion in the Forefoot and Tibia during Treadmill Walking:

Shannon Mullaney BS, Géza Kogler PhD, CO, LO

Background: Lower limb orthoses are commonly prescribed to assist patients with biomechanical deficits to restore functional mobility. However, in some instances they may also impose undesirable perturbations. A clear characterization and understanding of the movements of terminal stance are not well described.

Methods: Inertial measurement units (IMUs) were affixed to custom molded interface fixtures to quantify movements of the forefoot and tibia respectively. Data from the IMUs were collected and recorded through the Vectornav Software. Subjects walked barefoot (unconstrained control) on a single belt treadmill at 1.0 m/s as motion data was collected. Subjects then donned a sandal with an incorporated Otto Bock X-Firm carbon fiber footplate (to constrain foot motion) and again walked on a treadmill at 1.0 m/s while data was collected from the IMUs.

Findings: The results of this pilot study preliminarily suggest similar patterns of motion between subjects in the forefoot and tibia during barefoot walking. There are notable differences in the motion path of the forefoot and tibia when comparing the barefoot control and constrained foot conditions. The preliminary results suggest the greatest compensations for a constrained forefoot occur in the coronal plane for both the tibia and forefoot segments.

Interpretation: The data support the idea of a third rocker as described by Perry but suggests the rocker motion is created in multiple cardinal planes. The IMU measurement system may be used to collect multiple cardinal plane motion of a subject while walking with various rocker sole and orthoses designs. The instrumentation has the potential to determine how effectively a footwear system may restore natural rocker motion during terminal stance phase of gait.

Introduction

A thorough understanding of the gait cycle is required for Orthotic and Prosthetic practitioners to ensure their prescribed devices meet the movement goals of the wearer. A clinical standard for defining the gait cycle has been described by Perry as a stance and swing phase with multiple divisions within each phase (Perry and Burnfield 2010). Four rockers occur during stance and are defined as heel (first) rocker, ankle (second) rocker, forefoot (third) rocker, and a recently defined toe (fourth) rocker (Perry and Burnfield 2010). Third rocker occurs during terminal stance and includes the strongest propelling force when the body weight falls beyond the support area of the foot (Perry and Burnfield 2010). During this propulsion, the first ray plantarflexes and everts (Cornwall and McPoil 2002) acting as a rigid lever for the body to roll over. When patients are fit with a lower limb orthosis with a full length foot plate designed to control foot motion, the roll over during terminal stance may be perturbed. A study by Wu et al (2004) reported that "a rocker sole can be added to the plantar surface of the shoe to mimic the action of the forefoot joint, aid in roll over, and simulate forefoot dorsiflexion". The research by Wu et al (2004) also noted the "results indicate that there is a need to assess the effects of shoe modifications to consider more than single joints to fully reveal detailed biomechanical effects". Studies have examined forefoot motion in relation to the hindfoot or tibia during third rocker (Wright et al 2011; Jenkyn and Nicol 2007) but a full understanding of the movements of terminal stance are not well known or described. The emergence of evidence-based practice in medicine and allied health care, has challenged the profession of Orthotics and Prosthetics because the profession lacks an evidence basis for the motion control performance of footwear systems used in conjunction with lower limb orthoses. As such, there is a need for experimental research to validate commonly used lower limb orthoses and footwear systems provided as part of a treatment plan in clinical practice.

The aim of the pilot study was to develop a wearable test apparatus to understand and characterize the path of movements of both the forefoot and tibia during barefoot treadmill walking so that we may begin to determine the influence of movement constraint at the metatarsophalangeal joint. The research team believes the system can be used in future studies to measure forefoot and tibia motion when a footwear system is introduced to alter stance phase roll over. By measuring the motion a subject elicits when walking with various rocker sole shapes, data will be available to support the practitioner's claim that the rocker sole helps restore rocker motion. We hypothesize that at terminal stance the rocker action at the metatarsophalangeal joint during barefoot walking can be collected by an inertial measurement unit and that the collected data can then be used to quantify movements in the three cardinal planes. We also believe that orthotic constraint of motion of the foot with a rigid composite foot plate will elicit a change in timing and/or magnitude of movement during stance phase in the tibia, forefoot or both the tibia and forefoot compared to the barefoot control (no orthotic constraint of the foot).

Methods

A new test apparatus was required to measure motion in three dimensions of the forefoot and tibia during gait. In order to accurately measure three dimensional motion, two VN-100 Rugged Inertial Measurement Units (IMU) (VectorNav Technologies©, Richardson, TX, USA) were used. An additional component was developed to allow force sensing resistors (Interlink Electronics, Camarillo, CA, USA) to attach to the plantar side of the foot to act as switches that signal transitions between the different phases of gait. The force sensing resistors are not used in this study but are discussed and will be used in future work.

Test Apparatus Construction

The construction of the test apparatus began with a negative impression of the lower limb shank and midfoot taken from an average-size subject. The impression was taken to make the system fit the anatomical contours of a person's leg. The negative impression was then transferred to a positive model and modified similarly to a solid ankle foot orthosis. Then cuffs were thermoformed from modified polyethylene for both the tibial and forefoot sections.

The cuffs are specially designed to accommodate a variety of limb shapes and prevent motion between the skin and the test apparatus. The cuffs are intended to wrap around ≥50% of the limb segments' circumference. This design provides a firm hold and prevents rotational motion by compressing the soft tissue on the posterior aspect of the shank. The trimlines and contours are designed to avoid bony prominences such as the malleoli and to provide flexibility to the design. The edges of the distal tibia section flare away from the shank to prevent discomfort for the subjects. Both tibial sections are lined with Spenco®, a neoprene material with fabric on one side which is commonly used as an interface lining of foot orthoses. Spenco® was used with the neoprene side towards the skin to increase friction and prevent rotational motion from occurring between the subject's limb and measurement apparatus.

Test Apparatus Design

The measurement apparatus is composed of two sections: a tibial section and a forefoot section. The tibial section is divided into a proximal cuff and a distal cuff which are connected by a metal rod attached to the plastic with metal slots and set screws (**Figure 3**). Dividing the tibial section into two pieces allows for greater adjustability in the design and accommodation of a variety of patient heights. The cuffs can slide on the metal rod by loosening the set screws and then be positioned at the desired location based on the height of the subject. Once the set screws are retightened the cuffs are no longer moveable. An L-bracket can be mounted to the metal rod and contains the cables necessary to read the force sensor data as seen in Figure 3. The tibial section is held to the shank by two Velcro straps on the proximal cuff and one on the distal cuff. The Velcro also allows for the tension to be adjusted fitting an individual subjects needs.

Figure 3. Tibia and Forefoot Cuffs with attached Inertial Measurement Units (IMUs).

The forefoot section is comprised of only one cuff that mounts around the mid-foot as seen in Figure 1. The forefoot cuff is not lined to prevent the material thickness under the foot from causing undesired deviations to the subject's gait. A small screw threads through the plastic cuff to attach the IMU mount. The subject's foot is protected from the screw head by a foam pad. The forefoot cuff was taped to the foot to eliminate artifact motion caused by the change in foot shape.

The IMUs are attached to small metal plates that are screwed onto the threaded mount of a camera tripod. The camera tripod has a swivel head that allows for 360^{o} of motion in all planes which allows the IMU to be leveled to neutral with the ground. Circular bubble levels attached to the IMUs serve as guides to level the unit as a baseline starting point for all subjects. The camera tripod can be unlocked and the angle can be adjusted and locked in the desired alignment. The tibial IMU is mounted to the metal rod that connects the two cuff sections. The mount for the forefoot IMU is thermoformed into the plastic cuff to reduce bulk and weight at the distal end of the foot. A light weight device is important to ensure gait is only altered by the desired variables introduced by the research team. The forefoot cuff weighs 0.09kg and the tibial section weighs 0.37kg and together are believed to add an inconsequential weight to the subject when they walk with the technology.

An additional component was designed to attach two force sensing resistors (FSR) to the plantar surface of the foot to act as switches. One FSR can be taped to the heel to mark the beginning of stance phase. The second FSR can be taped to the plantar aspect of the first metatarsal head to mark midstance and the end of stance.

Sandal Design and Fabrication

Custom sandals were designed in four sizes to attach the rigid foot plate to the subjects with minimal intervention and accommodate feet in lengths from 22 cm to 31 cm. The sandals are designed to be donned over the forefoot cuff, which is contoured to the foot, but still provide an attachment for the rigid foot plate. The sandal consists of an Otto Bock Very Firm carbon foot plate attached to a thin piece of non-slip material with extensions for strap attachment as seen in **Figure 4**. Four Velcro straps are riveted onto the distal extensions to allow for adjustments for fit and comfort of the sandal. The strap placement is designed to wrap around the forefoot cuff so the cuff would not have to be repositioned between test conditions. This design feature eliminates human error in repeating placement of the cuff between test conditions. An elastic heel counter is integrated into the posterior aspect of the sandal as seen in Figure 2. The flexibility of the elastic heel counter acts to suspend over the calcareous rigidly attaching the foot plate to the foot and can be adjusted to accommodate a variety of foot shapes and sizes. The research team believes the sandal will not introduce any other variable to alter the subjects gait because they sandals weigh 0.13-0.17kg and the mass should not have a significant influence on subject's gait.

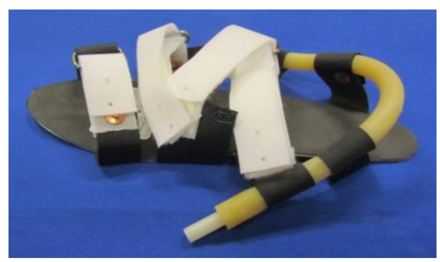

Figure 4. Custom fabricated sandal with contoured carbon fiber foot plate, non-slip sole, Velcro closures and elastic heel counter.

Subjects

Three subjects participated in this study that was approved for human subject research by the Georgia Tech Institutional Review Board. All subjects were healthy and able-bodied with no reported or observed foot or ankle pathologies in the past 12 months. Subjects were given instruction with what to expect during data collection and were allowed to ask any questions before beginning the session.

Testing Protocol

Prior to the subject's arrival, the inertial measurement units were connected to a computer and a program developed by VectorNav Technologies© which was used to collect and record the data transmitted from the IMUs. The IMUs were then connected to the metal plates on the tibia and forefoot cuffs.

When the subject arrived, they were instructed on what to expect and how the testing session would proceed before donning the device or beginning the data collection. The subjects were given time for questions and to discontinue the testing session if desired. The tibial and forefoot cuffs were then donned by the research team and the subject began walking on the treadmill at 1.0 m/s until they reported feeling comfortable with the speed and testing conditions.

The subject then stopped walking and began the barefoot test condition. The subject was instructed to stand comfortably on the treadmill and look at the wall in front of them. The researcher used circular bubble levels attached to the IMUs to level them to a neutral starting point. Using the bubble levels provided a common starting point across all subjects and test conditions. The subject then restarted walking and reported when they felt comfortable. Three trials of data were collected with 15 steps per collection. The subject was not informed when the data was being collected to eliminate any changes in gait caused by knowing they were being tested. After the third data collection the test condition was terminated, the subject stopped walking and the next test condition would begin.

The rigid sandal was then donned over the forefoot cuff by the researcher with the subject seated on the side of the treadmill. Then the subject began walking at a low self-selected speed and increased to 1.0 m/s as they felt comfortable. Time was allotted for the subjects to acclimate to the new testing conditions while walking with the rigid foot plate. The three trial data collection was repeated the same way as the barefoot control condition. After the three trials were completed the subject was instructed to cease walking and sit down. The cuffs were removed by the research team and the testing session ended.

Results

Forefoot Results

The results of this preliminary pilot study demonstrate trends in the data and differences in forefoot motion between the control and constrained conditions. The general pattern of motion for the forefoot appears similar (i.e., minimal difference) between subjects although the timing or magnitude demonstrate individual differences in barefoot conditions in all planes as seen in **Figure 5**.

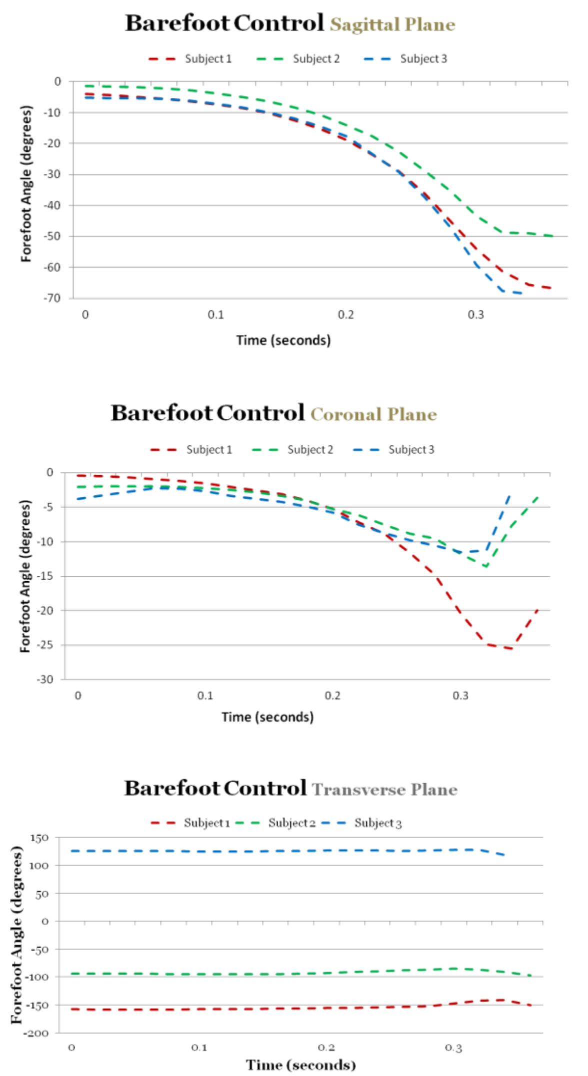

Figure 5. From top to bottom the graphs show forefoot motion during control condition (i.e., barefoot walking) for three subjects in the sagittal, coronal, and transverse planes respectively.

The motion of the forefoot in all planes appears to follow an arc pattern of motion with individual variations beginning during the last 15% of the terminal stance phase. In the sagittal plane the three subjects appear to follow a similar, normal arc of motion for the first 88% of the terminal stance phase. All subjects follow a pattern of increasing plantarflexion in the forefoot with the peak plantarflexion occurring at toe off. The subjects' forefoot at the MTP joint moves through a range of ~46^{o}, ~43^{o}, and 36^{o} respectively over the same amount of time until the 88% point where each subject shows variation. Individual variation appears to begin at ~94% of terminal stance in the coronal plane after following an arc motion. The arcs appear to be subject specific but display similar patterns at the start of terminal stance. All subjects begin in a position of inversion and move through a pattern of increasing inversion to a peak and then returning toward a neutral coronal plane alignment. The range of motion observed in the transverse plane appears to be much smaller than that observed in the other two coordinate planes (i.e., coronal and sagittal). All subjects remain in neutral rotation until about 83% of terminal stance at which time they move into slight internal rotation followed by external rotation back to neutral at toe off.

When the rigid foot plate is introduced (i.e., constrained condition) there is a notable change in the elicited pattern of motion of the forefoot when compared to the control condition (i.e., barefoot) in both the sagittal and coronal planes. However, the type of change varies between subjects. For the sagittal plane, two subjects changed the timing of their pattern of motion while the third subject changed the magnitude of motion.

As seen in **Figure 6** below, there is a noticeable difference between the forefoot motion in the barefoot and rigid foot plate conditions in the sagittal plane. All subjects still demonstrate an arc pattern of motion at the start of terminal stance but the radii of the arcs have changed from the barefoot control to the rigid foot plate condition. Subjects 1 and 2 have increased their arc radii which appears as a more gradual slope on the graph. The peak plantarflexion angle of the two subjects is lower but required a longer time to achieve in the constrained condition when compared to the barefoot control. Subject 3 demonstrated a decreased arc radius and appears to elicit a steeper slope to the pattern of motion. The third subject also appears to reach a higher peak plantarflexion angle in a shorter time in the constrained condition than the barefoot condition.

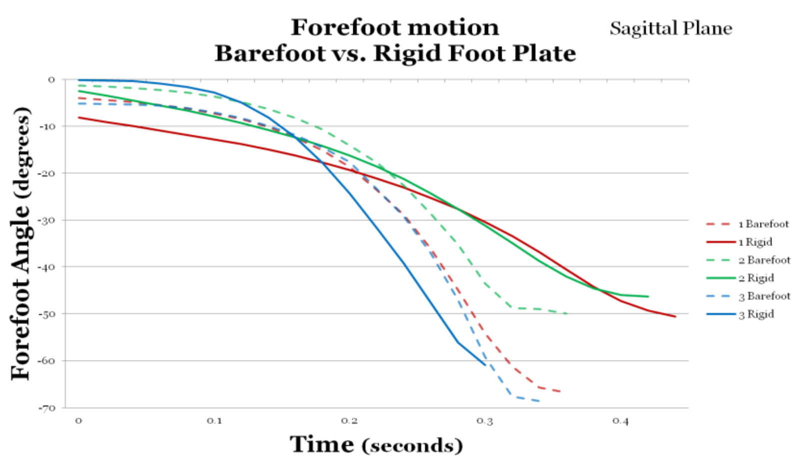

Figure 6. This graph shows forefoot motion in the sagittal plane comparing the barefoot control condition (shown by the dashed lines) and the constrained rigid foot plate condition (shown by the solid lines).

The greatest influence of constraining motion of the metatarsophalangeal joint occurs in the coronal plane compared to the barefoot control. A visible change in movement pattern in the coronal plane is observed and characterized by a loss of inversion motion when the foot movement is constrained compared to the control as seen in **Figure 7**. The barefoot condition, as seen by the dashed lines on **Figure 7**, shows the forefoot moving in a pattern of increasing inversion until a peak about 88% through terminal stance when the foot begins to decrease the amount of inversion back toward a neutral coronal angle at toe off. In the constrained condition the forefoot appears to lose much of the inversion from the barefoot control and moves toward eversion at the end of terminal stance and toe off.

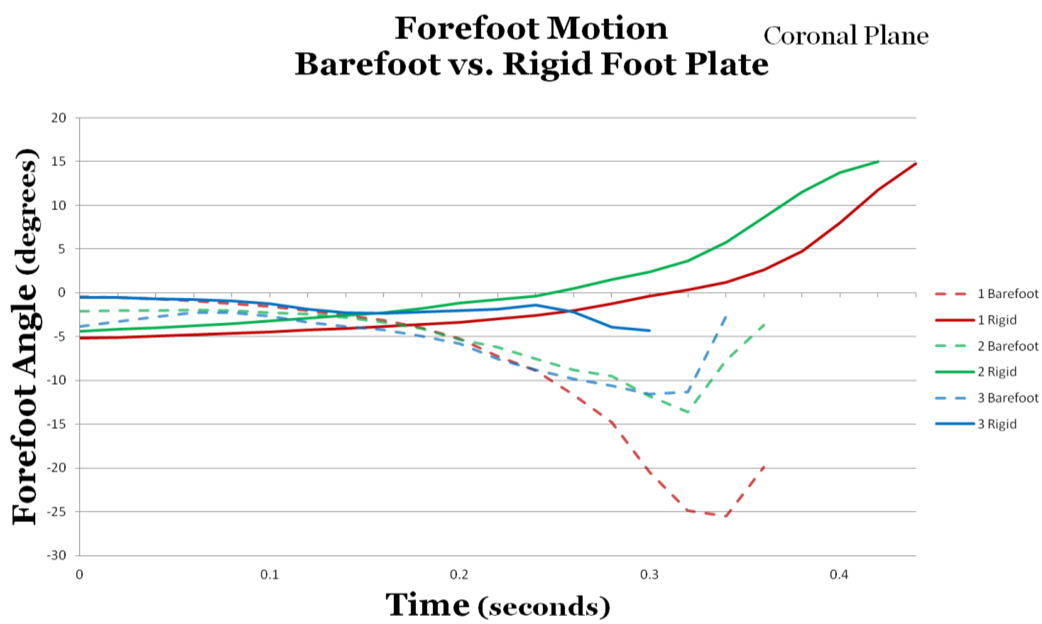

Figure 7. This graph shows forefoot motion in the coronal plane comparing the barefoot control condition (shown by the dashed lines) and the constrained rigid foot plate condition (shown by the solid lines).

Less variation occurs in the transverse plane during terminal stance. The forefoot remains in a neutral position in the transverse plane and then externally rotates at the end of terminal stance and the beginning of toe off. When the constraint is introduced a similar pattern of motion is followed but the magnitude of angular change between the conditions changes. While the pattern of motion is similar between subjects, two of the three subjects increase their step time and one subject decreased the step time.

Tibia Results

The motion of the tibia appears to follow similar characteristics as seen in the forefoot. First, the tibia appears to travel in an arc pattern of motion for the first ~75-85% of the terminal stance phase in all planes. The individual subjects show variability during the last ~15-20% of terminal stance and may differ in timing or magnitude of the arc. Sagittal plane motion of the tibia seems to follow the same arc for all three subjects with about 30° range of motion during the first 83% of the phase. The coronal plane shows more variety in the pattern of motion between subjects but all subjects motion follows a curved path until the transition point at about 88%. The tibia follows the same pattern of motion in the transverse plane as the forefoot where it remains in neutral rotation until ~72% of terminal stance at which time it externally rotates until toe off.

With the introduction of the rigid foot plate, there was a noticeable change in the pattern of motion of the tibia when compared to the barefoot control condition. The pattern of motion of the tibia in all three planes was similar between the two test conditions but the magnitude of motion changed between the constrained and unconstrained conditions. All three subjects increased the magnitude of motion but only two of the three increased the length of time over which the motion was completed. As was seen in the forefoot, the greatest influence of constraining the forefoot appears to have occurred in the coronal plane of the tibia. The tibial pattern of motion in the coronal plane during the constrained condition is similar to the pattern of motion observed in the barefoot condition but the magnitude has greatly changed as seen in **Figure 8**.

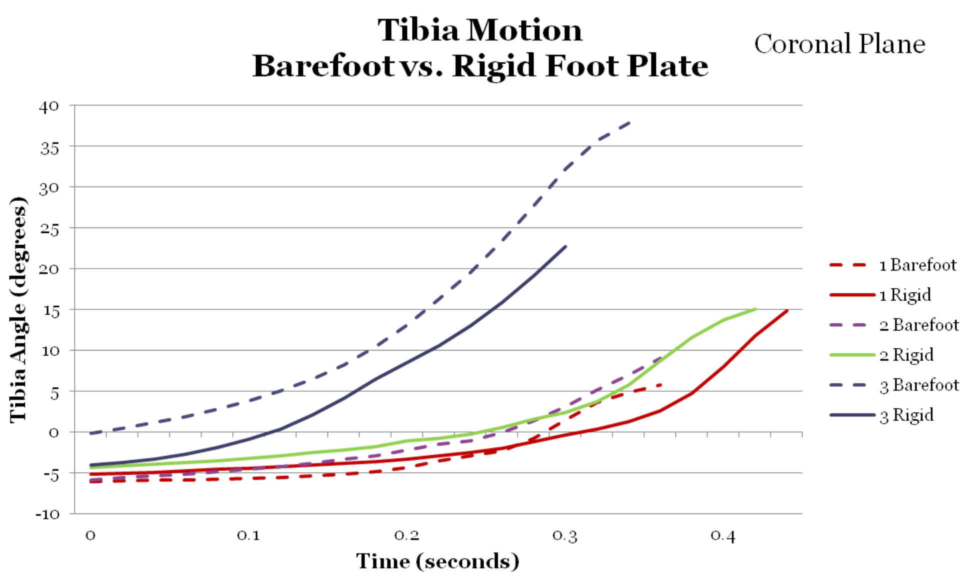

Figure 8. This graph shows motion of the tibia in the coronal plane during both the barefoot control condition (dashed lines) and constrained/rigid foot plate condition (solid lines).

Figure 8 shows tibial motion of the three subjects in both the barefoot (dashed line) and constrained (solid line) conditions. There is an obvious difference in the final angles reached within each subject between the two conditions.

Discussion

The motion of the forefoot during both the barefoot control and orthotic constrained conditions supports the concept of a forefoot rocker as outlined by Perry and Burnfield (2010). A rocker can be described as "a curved piece of wood or metal on which an object (such as a cradle or chair) moves back and forth or from side to side" (Merriam-Webster 2012). The previous definition suggests a rocker is one dimensional (i.e., uniplanar) but the data presented supports a multi-planar rocker motion elicited during terminal stance. The results show an arc pattern of motion for the forefoot in three planes suggesting a rocker is occurring simultaneously in all planes. **The findings from our research regarding three cardinal plane analysis is novel compared to conventional biomechanics literature that traditionally reports on a single plane (i.e., cardinal sagittal plane) when characterizing the foot and ankle kinematics during stance phase of gait.**

During the barefoot walking condition, the forefoot ends in a position of plantarflexion and external rotation which is supported by a study conducted by Leardini et all (1999). The paper by Leardini et al (1999) measured ankle motion and states at toe off the ankle is in a position of external rotation and dorsiflexion. When correlated to the segmental measurements in this study, dorsiflexion of the ankle is the same as plantarflexion of the forefoot which matches the results of a previously published study.

When the forefoot constraint is introduced the pattern of motion in all planes is disrupted as hypothesized. The foot is a multiple segment complex consisting of 26 bones and 33 joints that function in unison to support and propel the body. This intricate design leads to individual differences in subjects that account for the variation in the motion pattern elicited in the barefoot condition and the disruption of motion observed in the constrained condition. If all the bones and joints are not able to function in a coordinated fashion, then other areas of the foot may compensate and the trajectory of motion is likely to change. The compensation is best described from the coronal plane results of the forefoot. During the barefoot condition the subject moves through a pattern of inversion followed by a return toward the neutral alignment and eventually rolling off the first metatarsal and hallux at toe off. When the rigid foot plate is introduced all subjects display a loss of inversion and elicit a pattern of continuing eversion until toe off. Our interpretation of this finding is that it is a compensation strategy that allows subjects to achieve the shortest path to roll over. As seen in **Figure 9**, the red arrow signifies the normal path of motion for the foot and the blue arrow shows the disrupted path of motion. When the forefoot joints are constrained, the subject will naturally alter their gait to roll over the medial aspect of the first metatarsal as opposed to rolling over the now locked first metatarsophalangeal joint because it is the shortest unconstrained distance.

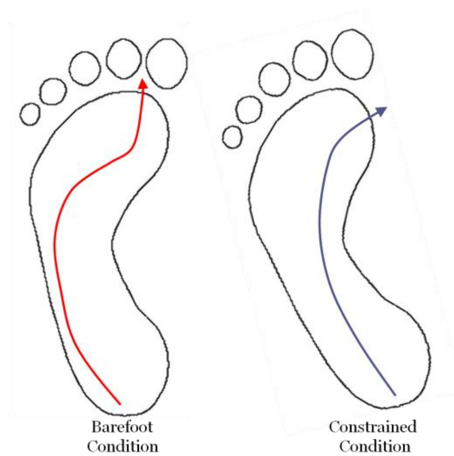

Figure 9. This picture shows the estimated trajectory of the center of pressure of the foot during the barefoot and constrained conditions.

The preliminary results from this pilot study demonstrate notable trends in the data that have been interpreted and related to clinical outcomes. The data collected measures the change in motion of the IMU, which is attached to the limb segments. As the investigation is ongoing, the research team suggests the measured angles can be translated to measured angles of the forefoot and tibia because they are solidly linked to the IMUs. Further studies and analysis are required to conclude the system described in this investigation represents the true motion of the limb segments. Further limitations include the small sample size and inability to compare measured values with literature because the measurements were taken in the global reference frame. Another limitation to this study is the high cost of the inertial measurement units which may make this system less useable in a clinic setting.

Acknowledgements

This project received funding from the Pedorthic Footwear Foundation.

Conflict of Interest

There were no conflicts of interest with any financial or personal relationships that could influence or bias this work.

References

1. Cornwall M, McPoil T., 2002. Motion of the Calcaneus, Navicular, and First Metatarsal During the Stance Phase of Gait. Jour of Am Pod Med Assoc. 92, 67-76.
2. Dixon, P.C., 2012. Ankle and midfoot kinetics during normal gait: A multi-segment approach. Journal of Biomechanics. Jour Biomech. 10,
3. Jenkyn TR, Nicol AC., 2007. A multi-segment kinematic model of the foot with a novel definition of forefoot motion for use in a clinical gait analysis during walking. J Biomech. 40, 3271-3278.
4. Leardini, A., Benedetti, M.G., Catani, F., Simoncini, L., Giannini, S., 1999. An anatomically based protocol for the description of foot segment kinematics during gait. Clinical Biomech. 14, 528-536.
5. Long, J.T., Klien, J.P., Sirota, N.M., Wertsch, J.J., Janisse, D., Harris, G.F., 2007. Biomechanics of the double rocker sole shoe: gait kinematics and kinetics. J. of Biomech. 40, 2882-2890.
6. Perry J., Burnfield J., 2010. Gait Analysis Normal and Pathological Function, second ed. Slack Incorporated, NJ
7. Merriam-Webster, 2012. Dictionary. http://www.merriam-webster.com/dictionary/
8. Wright C.J., Arnold B.L., Coffey T.G., Pidcoe P.E., 2011. Repeatability of the modified Oxford foot model during gait in healthy adults. Gait & Posture. 33, 108-112.
9. Wu W.L., Rosenbaum D., Su F.C., 2004. The effects of rocker sole and SACH heel on kinematics in gait. Med. Eng. & Phys. 26, 639-646.

Summary:
The lines of work performed by the funded research represent an extensive collaboration among three research laboratories at Georgia Tech. The outcome of the project unveiled important discoveries.

1.) First, a new rocker profile was not only designed, engineered, and created but we produced data to validate the performance of the footwear system to restore roll over despite constraint of ankle-foot motion by an AFO-footwear system used by a cohort of five subjects walking for an extended duration. This discovery represents new knowledge that is important, especially because there is little current knowledge that describes design features and reports the biomechanical influence of the features in a cohort of subjects using the technology.
2.) Second, the research revealed that constraint of forefoot motion during stance phase elicited a multiple-plane response of movement. This discovery is important because typical research examining roll over characteristics during stance phase has traditionally focused on a single plane of movement (i.e., sagittal plane) whereas the current research evaluated multiple planes of motion and revealed a new finding.

With funding from AOPA-COPL, we were able to establish a footwear system design and to develop research protocols to advance knowledge of the influence of constraint of movement of the lower limb and the performance of engineered footwear systems to restore roll over during stance phase of gait. Based on the new knowledge, we will now need to consider implementing a multiple plane motion data collection system to record movement responses to constraint of ankle and foot motion and the performance of a footwear system to restore stance phase roll over.

Eventually, we aim to expand this research to assist the orthotist in better understanding the optimal orthosis/footwear combination as a clinical treatment for locomotor rehabilitation.