ABSTRACT

ABNORMAL GROUND REACTION FORCES IN INDIVIDUALS WITH UNILATERAL TRANSTIBIAL AMPUTATIONS

Background: The number of persons living with transtibial amputations (TTA) in the United States is expected to more than double in the next 45 years due to an increase in aging population and dysvascular diseases. Because of this, it is important for medical professionals to understand the common impairments associated with this population. There is a lack of comprehensive research documenting the ground reaction forces (GRFs) during gait in this population.

Objective: The purpose of this research is to study the multi-directional GRFs during gait in persons with TTA.

Methods: Eight adults with unilateral TTAs participated in this study. Ground reaction forces were measured using a Kistler platform.

Results: A t-test was used to determine significant GRF variability between limbs. P-values were significant during loading response in the medial lateral plane (p = 0.0008) and the vertical plane (p = 0.0157.) There were no significant findings during mid-stance. P-values at terminal stance were significant in the medial lateral plane (p = 0.0028.)

Discussion: There are asymmetrical ground reaction forces associated with having a TTA amputation that most significantly effect loading response and terminal stance. Correcting these asymmetries should be the focus for physical therapy interventions in this population.

Nicholas Cameron Ward
May 2018
ABNORMAL GROUND REACTION FORCES IN INDIVIDUALS WITH UNILATERAL TRANSTIBIAL AMPUTATIONS

by
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A project submitted in partial fulfillment of the requirements for the degree of Doctor of Physical Therapy in the Department of Physical Therapy College of Health and Human Services California State University, Fresno
May 2018
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BACKGROUND

Prevalence of Lower Extremity Amputation

There are nearly 2 million people living with amputation in the United States, with approximately 185,000 new lower extremity (LE) amputations occurring each year.\textsuperscript{1} The most common causes for lower limb amputation (LLA) are dysvascular (54%), traumatic (45%), and cancerous (<2%) pathologies.\textsuperscript{1} Over the next 45 years the number of persons living with amputations is expected to more than double due to the increasing prevalence of dysvascular disease and continued upward trends of the aging population.\textsuperscript{1} The most common level of amputation is to the shank, also referred to as transtibial amputation (TTA) or below the knee amputation (BKA).\textsuperscript{2} This lifechanging surgery can lead to a host of other increased health risks such as decreased function, osteoarthritis, increased BMI, and early mortality.\textsuperscript{3-8}

Transtibial Amputation

The individuals at the highest risk for an amputation are those with a history of vascular disease such as peripheral vascular disease (PAD), coronary artery disease (CAD), or diabetes.\textsuperscript{1-4} Having an amputation with these comorbidities can have a severe impact of the time to recover and functional capacity of individuals after an amputation.\textsuperscript{9} On the other hand, traumatic amputations typically have greater functional outcomes usually due to the higher level of function to start and decreased comorbidities.\textsuperscript{9} This has been quantified by measuring energy consumption and kinetic variables between these 2 groups.\textsuperscript{3,9}

Depending on the individual, having an amputation can have varying effects on their level of function. Some individuals can participate fully in all the activities they previously used to participate in, some become wheelchair bound,
and many of the other individuals fall somewhere inbetween. Improving their level of function should be a major goal in rehabilitation for this population.

Amputations can occur at any level of the LE, and there is extensive literature on the different areas that they can occur. There are certain basic principles that must be considered when deciding to amputate a limb. For instance, there must be proper circulation to the area of amputation to restore proper healing. In persons with trauma, it may be necessary to perform an above the knee amputation, even if some of the tibia is salvageable. This is due to a need to provide a long enough residual tibia to allow for placement into a socket as well as an adequate lever arm.

There are multiple surgical procedures that can be considered when performing a TTA. These procedures include a Modified Burgess Posterior Flap Surgery, Modified Bruckner Procedure, or a Modified Ertl Procedure. The specifics of these procedures vary, however there are certain preferred characteristic values shared between them. These include sparing the proximal third to half of the tibia, beveling the tibia, and shortening and securing the residual fibula. If these certain stipulations can be met, the outcomes and functioning of the residual limb can be more successful.

Sequel of Osteoarthritis Diagnostic Patterns

Osteoarthritis (OA) is a leading cause of pain and disability in the United States and leads to reduced quality of life. OA is defined by focal areas of articular cartilage loss within synovial joints which is associated with joint narrowing, hypertrophy of bone, thickening of the capsule, pain, stiffness, and limitations in range of motion (ROM). The joint most commonly affected by OA is the knee.
OA is diagnosed either clinically or radiographically. Clinical diagnosis of OA is defined by presence of at least 3 of 6 of the following risk factors: age > 50 years, stiffness of the knee < 30 minutes, crepitus, bony tenderness and bony enlargement at the knee, no palpable warmth. The classic determination of knee arthritis radiographically is through the use of the Kellgren-Lawrence scale. The scale is rated from 0-4 diagnosing OA in a progressive manner.

A grade 0 represents no radiographic features of OA and, grade 1 exhibits possible joint space narrowing and osteophyte formation. Grade 2 is defined by osteophyte formation with possible joint space narrowing while grade 3 shows multiple osteophytes, definite joint space narrowing, sclerosis and possible bony deformity. Finally, grade 4 shows large osteophytes, marked joint space narrowing, severe sclerosis and definite bony deformities. Scores that range from 2-4 confirm diagnosis of OA. Both approaches are effective methods of diagnosing OA.

Risk factors for developing OA include: increased BMI, previous knee injury, age, being female, impaired biomechanics, increased joint loading, genetics, and muscle weakness. These factors are important when considering risk in patients with amputations because following an amputation joint loading, impaired biomechanics, and asymmetrical strength are specific concerns in this population of patients.

The Knee

The knee is a critical component of human locomotion. It is the basic determinant of limb stability during stance phase. Furthermore, knee flexibility is the primary factor in the limb’s ability to advance forward, allowing for adequate foot clearance during swing phase. Knee flexion and extension during gait
occurs in a range from 0-70 degrees, with 60 degrees being necessary for adequate toe clearance during swing.\textsuperscript{18} Transverse rotation also occurs at the knee with an average rotation of 9 degrees. Maximum external rotation is achieved at the end of stance phase and begins internally rotating at terminal stance all the way through to loading response. Coronal plane motion occurs as well with both abduction and adduction. Maximum knee abduction occurs at initial contact with maximal knee adduction occurring during swing.\textsuperscript{18} Persons with a TTA are less likely to utilize their full range of motion of the residual knee during gait.\textsuperscript{19}

**Normal Gait**

Typical gait is comprised of a repetitious sequence of limb motion to move the body forward.\textsuperscript{18} It is characterized by synchronous, regular, and progressive movements and is usually separated by 2 phases: stance and swing.\textsuperscript{18,20,21} Stance phase is approximately 60\% of the gait cycle and swing phase is approximately 40\%.\textsuperscript{18} Abnormal gait diagnosis is confirmed by comparison to normal gait patterning. Once atypical patterning is confirmed the consequences associated with it are apparent.

The 2 major classification systems for normal gait include the traditional and the Ranchos Los Amigos Medical Center (RLAMC). The traditional system breaks up gait into stance phase and swing phase with stance phase consisting of heel strike, foot flat, mid-stance, and heel off. There are problems inherent with this classification system because when looking at pathological gait not all phases may be present. RLAMC classifies stance phase into initial contact (IC), loading response (LR), mid-stance (MSt), terminal stance (TSt), and pre-swing (PSw.). Swing phase is also sub-classified in to initial swing (Isw), mid-swing (MSw), and
terminal swing (TSw.) Although both classification systems are similar, Ranchos scale has been shown to be the more accurate description of gait.\textsuperscript{18,21,22}

The gait cycle (GC) can also be defined by the 3 major tasks involved during locomotion and when they occur: weight acceptance, single limb support, and limb advancement. Each of these play a critical role in normal human gait.\textsuperscript{18} Weight acceptance is comprised of initial contact (0-2% GC) and loading response (0-10% GC.) Single limb support is comprised of mid-stance (10-30% GC) and terminal stance (30-50% GC.) Limb advancement consists of pre-swing (50-60% GC), initial swing (60-73% GC), mid-swing (73-87% GC), and terminal swing (87-100% GC).\textsuperscript{18}

Lastly, there are 3 basic requirements for normal human gait: progression, stability, and adaptation.\textsuperscript{21} Progression refers to movement of one’s body in a particular direction. Stability refers to a person’s ability to maintain body support. Adaptation refers to manipulation of one’s gait in responses to environmental demands.\textsuperscript{21}

**Impairments in Persons with TTAs**

Persons with TTAs have strength discrepancies between limbs, with their uninvolved limb being stronger than the prosthetic limb.\textsuperscript{8} This leads to asymmetrical bodyweight distribution with their center of pressure (COP) shifted anterolaterally towards the uninvolved limb.\textsuperscript{23} In persons without amputation the COP is typically in the center of their base of support, thus creating symmetrical body weight distribution.\textsuperscript{18} Symmetrical weight distribution is a critical component of gait efficiency and helps prevent mechanical degradation of the joints. Because individuals with a TTA are more susceptible to these asymmetries they are also more susceptible to diminished gait efficiency and joint degradation.
This asymmetry of bodyweight distribution contributes to gait abnormalities as well. Individuals with TTAs have decreased limb symmetry during gait, reduced loading of the prosthetic limb, and increased weight bearing on the intact limb. Furthermore, this contributes to the gait impairment of increased lateral trunk flexion towards the prosthetic side and gluteus medius weakness. In typical gait, the gluteus medius stabilizes the pelvis and prevents the contralateral side from dropping during swing phase. When there is gluteus medius weakness the pelvis drops creating biomechanical dysfunction throughout the weightbearing limb. This impairment is likely responsible for the increased knee external adductor moment (KEAM) that is seen in this population.

During typical gait, at initial contact the tibialis anterior muscle acts as a shock absorber, assisted by the quadriceps eccentrically. The hip extensors also act as a shock absorber to the hip joint and prevent flexion at the hip during loading response. Because persons with TTAs have compromised anterior tibial and hamstring musculature, as well as a decreased biomechanical advantage of the quadriceps, they demonstrate diminished shock absorption during initial contact and loading response.

Of most notable importance of the gait dysfunctions is the increased KEAM and increased weight bearing on the intact limb. Studies have shown that persons with lower than normal adduction moments during walking are substantially less likely to develop knee OA. Because it has been shown that increased joint loading and impaired biomechanics are risk factors for developing OA, the probable outcome is that individuals with unilateral TTAs are also more likely to develop OA.

Other impairments associated with persons with TTAs are: reduced walking speed, reduced power generation during the propulsion phase of gait,
reduced knee flexion during loading response, decreased push-off force on the prosthetic limb increased medial/lateral ground reaction forces (GRF) and anterior/posterior GRF of prosthetic limb during braking phase, and increased energy cost. In typical gait the plantar flexors and knee extensors are the primary sources of forward motion. Because TTAs lack plantar flexors, the knee extensors become more important for producing forward progression. Increased hamstring activity during early stance may help to compensate for lack of plantar flexors by increasing hip extensor action.

Lastly, a common observation noted in the literature is the decreased step length on the prosthetic limb. This has been attributed to 2 main reasons. The first is that individuals with TTA are not able to create the same amount of push off power during terminal stance because they lack a gastrosoleus complex. Secondly, by decreasing step length it helps to increase their margin of stability. Therefore, it has been noted that certain asymmetries, like step length, are functional adaptations and may not be something to be addressed during treatment.

Prosthetic Considerations

Medicare K-Levels are used to determine the type of prosthetic components appropriate depending on the level of function of a person with a TTA or TFA. The classification system ranges from K0-K4 in ascending order of function and can be assessed using the Amputee Mobility Predictor outcome measure.

Prosthetic feet for persons with TTAs come in multiple designs and are based on activity levels. The most basic form of prosthetic foot is the solid-ankle, cushion-heel (SACH) which is prescribed for TTAs with a K1 level. This is used primarily for transfer and limited ambulation. Highest-level of prosthetic feet are
prescribed to persons with a K4 level. These are for specialized activities such as running, walking on uneven terrain, and sports. Neither of these types of feet were used by the participants of this study.

K2 feet are flexible and allow for soft plantar flexion and some transverse rotation. They are typically prescribed for persons who walk at a slow pace outdoors or mostly inside. K3 feet are normally reserved for persons with TTA that are regular community ambulators and walk with varying cadences. The majority of ambulatory persons with a BKA utilize either a K2 or K3 foot for ambulation and are therefore one of the primary demographics that physical therapists will work with.

In addition to the multiple types of prosthetic feet available, there are also many different prosthetic sockets. The most common socket types are a Patellar Tendon-Bearing socket, Total Surface-Bearing Socket, and a Hard Socket. Forces between the residual limb and the socket can alter mechanics based on multiple factors such as socket shape, wall height, and overall fit. Prosthetic socket design and fit are critical components of ensuring proper gait mechanics and stress the importance of collaborations between physical therapists and prosthetists.

**Ground Reaction Force During Ambulation**

The effects of body weight and force can be identified by the ground reaction forces (GRF) created during the stance phase of gait. These forces exist in 3 planes of motion: anterior-posterior (FX), medial-lateral (FY), and vertical (FZ). During propulsion, as weight is transmitted through the limb during contact, a force in the ground is created that is of equal magnitude but opposite in direction. GRFs are typically expressed as a percent of body weight (BW). Normal vertical GRFs during stance phase create a peak during loading response (110% BW), a
valley during mid-stance (80% BW), and another peak at terminal extension (110% BW.) Medial/lateral GRFs are typically only 10% of BW or less with peak medial force at loading response (5% BW) and peak lateral force in terminal stance (7% BW.) Anterior/posterior forces are equivalent to a maximum of 25% BW with peak anterior force during loading response (13%) and posterior shear highest at terminal stance (23% BW)\(^{18}\)

**Gaps in the Literature**

Studies on individuals with amputation have more recently focused on prosthetic biomechanics and kinetics. This is an important area of study, however the research on GRF data on persons with BKA is a critical component of determining how prosthetic changes can improve gait. Furthermore, many studies have been published on caloric expenditure during gait in persons with TTAs. Although these are both important at improving individuals with TTA quality of life and improving ambulatory abilities, there is limited literature available on GRFs. By collecting the GRFs associated with having a TTA, this research will help contribute to the direction of prosthetic design and physical therapy interventions.

**Purpose**

The purpose of this research is to determine GRFs associated with a BKA and the inherent differences between the intact and residual limbs. This will help add to the research literature on the GRF abnormalities of individuals with BKA that effect their experience during preferred walking speeds. The null hypothesis is that there will be no significant differences between GRFs of the intact and prosthetic limb. The alternative hypothesis is that there will be significant difference in GRFs between the intact and residual limb.
METHODS

Research Participants

Prior to collection of data, approval was obtained through the Institutional Review Board of California State University, Fresno. Subjects were random samples of individuals from the local community that volunteered to participate in this study. Inclusion criteria included age 18 and up, possession of a unilateral TTA, and able to stand for 20 minutes without an assistive device. Subjects were excluded from the study if they had any of the following: a surgical revision in the last 12 months, any open wounds or sores in the lower extremities, unable to walk without the use of an assistive device, unable to stand for greater than 20 minutes, having poorly controlled cardiovascular disease, history of active cancer (or cancer with/without treatment in the last 2 years), history of poorly controlled or brittle diabetes, and lack of verbal clearance for physical activity by primary care physician or orthopedic physician.

Protocol

All subjects completed forms including consent, release of liability, and answered questions based on current medical history. Height, weight, intact limb length, and residual limb length were recorded. Height was measured with a metric ruler against a wall from floor to top of head, with the subject standing flush against the wall barefoot. Weight was measured in Kg on the Kistler© Force Platform with a static stand of 5 seconds on a single force plate and with a separate scale measuring in pounds to compare for reliability. Segmental limb length was measured from center of greater trochanter to the lateral condyle, and distally to the apex of the lateral malleolus or most distal portion of soft tissue. All subject
information was entered with a code name, and physical copies of consent forms were kept in a locked cabinet at all times.

Prior to gait trials on the force platform, the Zenomat was calibrated through Protokinetic© software. Subjects began by walking 3 consecutive passes on the Zenomat pressure mat at their preferred walking pace to extract step and stride length. The Zenomat is similar to the Gaitrite, which is a valid tool for measuring both average and individual step parameters of gait and has excellent reliability.32,33

Wireless EMG electrodes were used to collect muscle activity during maximal volitional isometric contraction (MVIC) and during preferred pace ambulation.34 Skin was prepped for electrode placement by vigorous scrubbing for 15 seconds with an alcohol wipe over the gluteus maximus and gluteus medius. Electrode placement was determined based on Rainoldi et al (2004) and followed the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) recommendations.35 Bipolar surface electrodes (MVAP 1” x 1 7/8”, foam electrode with 2 snaps and 2 gel sites, 1 cm space between electrodes) were used. The sampling rate was set at 1000 Hz utilizing MyoResearch XPT™ from Noraxon (Noraxon USA, Scottsdale, Arizona). All raw myoelectric signals were pre-amplified with an overall gain of 1000. The common rejection ratio rate was set at 100 dB and signal to noise ratio <1 μV RMS baseline noise. The filter to produce a bandwidth was set at 10-1000 Hz.

Maximal GRF’s during each sub-phase of stance phase (loading response, mid-stance, and terminal stance) was calculated for each subject during each trial in the 3 planes of motion (anterior-posterior, medial-lateral, and vertical). These values for the intact limb and the prosthetic limb were compared to one another, as well as averaged across subjects. A two-tailed T-Test was then performed, which
compared the forces produced on the intact limb with those produced on the prosthetic limb.
RESULTS

Subject Demographics

Subjects were taken from the Fresno area using convenience sampling if they met the eligibility criteria. A total of 9 subjects participated in the study, 6 males and 2 females with TTA and 1 male with a transfemoral amputation (TFA). The person with a TFA was excluded from the analysis because of the inherent differences in gait between TTAs and TFAs. The cause of amputation varied from trauma to cancer, however no participant’s amputation was due to dysvascular disease. Average age was 54 +/- 11.35 years old and BMI was 29.58 +/- 4.39. Average length of the residual limb was 66.78 +/- 8.95 cm. and average years since amputation was 21.123 +/- 9.24. Table 1 includes subject demographics.

Electromyography

MVIC data were collected for all subjects at the beginning of each research session including 3 trials of maximum effort in 4 standardized positions to determine gluteus medius and gluteus maximus strength. Muscle activity was also recorded during gait trials and functional tasks (quiet standing, sit to stand, and single limb standing) during the treatment session. This information was saved to be analyzed later.

Zenomat and Ground Reaction Force Data

Prior to collecting data on the force plates, mean step length was measured using a Zenomat and measured using PKMAS software. A total of 3 trials across the Zenomat walkway were obtained. Step length data were collected for each subject to find a starting point on the walkway with the force plates. The starting
point to begin GRF data collection was marked with tape 3 steps back from the first force plate on the Kistler platform.

To analyze GRFs during gait 3 successful trials were obtained. A successful trial was determined if each foot made full contact with the appropriate force plate and the collector confirmed it was collected within the 30 second collection period. Trials were excluded if the subject did not make full contact with the force plate with both feet. Forces were collected in all planes (FX = anterior/posterior; FY = medial lateral; FZ = vertical) for both the intact limb and the prosthetic side and then averages were calculated for all subjects.

Average forces for loading response, mid-stance, and terminal stance for intact and prosthetic limb can be found in Tables 2-4. Images of the equipment used to collect data are found in Figures 1-2. Testing positions for MVIC testing are found in Figures 3-6. Visual graphs of the peak GRFs during loading response can be found in Figures 7-9.

A t-test was used to analyze the average GRFs on the intact limb versus the prosthetic limb for each of the 3 gait trials. Statistical significance was defined as a P value equal to or less than 0.05. During initial contact, the P values for FZ (vertical) and FY (medial/lateral) are 0.0157 and 0.00078 respectively demonstrating a high statistical significance. The p value for FX was 0.14 and therefore not statistically significant. No significant difference was found for any plane during mid-stance. During terminal stance, a significant difference was found in the FY plane with a P value of 0.0028 and no significance in the FX or FZ plane with p values of 0.391 and 0.112 respectively. Full values for these statistics can be found in Table 5.
DISCUSSION

Summary of Results

The purpose of this study was to collect and analyze GRFs and add informative data to the literature on force asymmetries in persons with unilateral TTAs. This study confirmed that there are GRF asymmetries between the prosthetic limb and the intact limb in individuals with TTA, therefore the alternative hypothesis was accepted. GRF asymmetry was found between limbs at initial contact in the Y and Z plane as well as during terminal stance in the Y plane. The null hypothesis was partially accepted because there was no statistical significance between the intact limb and the prosthetic limb during mid-stance, the Fx plane during loading response, and the Fx or Fz plane during terminal stance. Muscle activity and GRF data for functional tasks were collected but not included as they will be analyzed at another time.

The greatest significance of GRFs was found at initial contact. This can be attributed to multiple factors. There is a lack of ankle rocker on the prosthetic side, a decrease in muscle strength, increased pain, and/or abnormal mechanics of the residual leg. These can all lead to decreased loading of the prosthetic limb and may be the cause of the decreased GRFs observed.

There was not a statistically significant difference in every plane for every portion of stance phase, however there is a general trend of decreased forces on the prosthetic limb. The only exception to this was during mid-stance when GRFs were nearly symmetrical. However, just because there is symmetry of the GRFs does not prove that there are symmetrical biomechanics. Common compensations in persons with TTAs include a lateral trunk lean to prosthetic side which may attribute to the observed symmetry of GRFs during mid-stance.\textsuperscript{36}
Although the GRFs at mid-stance are not statistically significant, they are still clinically significant. Mid-stance is a portion of stance phase that is critically important to successful gait. It marks a point of advancement during gait where the leg is in single limb support for approximately 40% of the gait cycle. This means that the limb that is bearing all of the body weight needs to achieve an appropriate balance of stability and mobility to meet the demands placed on it. The population that we sampled from seems to be meeting that demand.

During terminal stance, because there is a lack of plantar flexors on the prosthetic limb the hip extensors have to compensate to generate forward propulsion. This may explain the trend of decreased vertical forces at terminal stance on the prosthetic side. Furthermore, because the intact limb is more pliable the transitions are smoother on the intact limb which may account for the significant findings of medial/lateral asymmetry during terminal stance.

**Osteoarthritis Risk**

Persons with unilateral amputations are more likely to develop OA on the uninvolved limb. Many of the risk factors for developing arthritis are common impairments seen in persons with amputations. The commonalities from the individuals in our study include increased weight bearing on the intact limb, being overweight, and increased age.

Increased weight and obesity are major risk factors for developing LE osteoarthritis. The mean BMI of our subjects was 29.58 putting them into the overweight category for BMI, almost in the obese category (BMI of 30 = obese). Because of the decreased mass of the residual limb, clinically they are more likely to be categorized in obese category.
Increased GRFs and abnormal joint loading are other causative factors for the early development of OA and knee pain. The subjects in this study were found to have a significantly increased GRFs on the intact limb during initial contact in the medial/lateral and vertical planes as well as during terminal stance in the medial lateral plane. This demonstrates increase of joint loading in the intact limb further demonstrates that this population is at greater risk of developing OA of the involved limb.

Cartilage degeneration is a natural consequence of aging.\textsuperscript{14,39} The average age of subjects in the study was 67 (6.55) putting them at greater risk of having or developing knee pain or OA of the intact limb. The average years since amputation was 21.125 (9.239). This shows that these subjects have been living with their amputations for more than half of their lives. Therefore, if their biomechanical impairments are due to their amputations, then they have had significant time to develop degenerative changes secondary to their gait irregularities.

The results of gluteal strength asymmetries of the participants of this study are unknown. However, it has been noted in the literature that muscle asymmetries are common among persons with LE amputations.\textsuperscript{8,16,17} It is important to consider that the prosthetic side is typically weaker, therefore persons with TTAs rely more heavily on their intact limb creating a greater risk for the development of OA.

\textbf{Literature on Ground Reaction Force Asymmetry}

The results from our research support previous researchers’ claims of GRF asymmetries in persons with TTA. The vertical GRF asymmetry is what has been most commonly reported amongst past researchers.\textsuperscript{19,25,40} Theories from this vary, however the most common explanation is that it results from a protective motor
strategy to protect the soft tissue of the residual limb because it is not suitable for load-bearing. To our knowledge, only 1 other study has found significant decrease in medial/lateral GRFs on the prosthetic limb. This research found during loading response the medial/lateral GRFs were diminished on the prosthetic limb. Our research found similar results, however we also found significant decrease GRFs during terminal stance in the medial/lateral plane. This is noteworthy because the GRFs may be even further asymmetrical than previously noted. Lastly, anterior/posterior GRF have been found to be asymmetrical in persons with TTA. Although, our research did not find statistical significance for this plane, it was approaching significance in during loading response (p = 0.14.) It is likely that if there was greater sample size or if the data were normalized that this difference would be significant as well.

In typical gait, the knee extensors and plantar flexors are the primary sources of propulsion. Because persons with TTAs are lacking plantar flexors, they rely more on their knee extensors to create forward progression. Because the knee extensors of the prosthetic limb are typically weaker, persons with TTAs tend to rely on their intact limb to produce forward momentum during locomotion which can be demonstrated by the increased GRFs on the intact limb. This is noteworthy, because the lack of specific anatomy is not a variable that physical therapists can change. Therefore, a consideration must be made for how persons with TTAs can best compensate for these discrepancies in GRFs. An intervention based study could help to better understand this dilemma and determine the extent that physical therapy can help address these impairments.

Also, because persons with TTAs are lacking plantar flexors, the hamstring and hip extensors are more active during terminal stance to generate forward movement. This increase in hamstring muscle activity from mid-stance to terminal
stance may also be the cause of the proportionally larger vertical GRFs when compared with the strength of the prosthetic limb.\(^{41}\)

Our findings were not statistically significant regarding GRF variability in all planes during mid-stance. Although not statistically significant, this is clinically relevant. If considered at face value, the findings of this research would suggest that mid-stance is an area of gait that is symmetrical. However, mid-stance kinematics have been previously researched in persons with a TTA and have found that there are discrepancies between intact and prosthetic limbs.\(^{19,42-45}\)

Common impairments during mid-stance include vaulting on the intact limb to provide limb clearance during swing phase of the prosthetic limb, Trendelenburg on the residual limb due to gluteus medius weakness, and lateral trunk lean during mid-stance on the prosthetic limb to compensate for residual limb weakness.

We are unable to say with certainty if the GRF symmetries during mid-stance were due to kinematic symmetry during gait or if the participants were compensating in some way to reproduce this symmetry. Therefore, conclusions from this study alone should not be made to assume that gait kinematics are symmetrical during mid-stance in persons with TTAs. These results do suggest however that loading response and terminal stance are of considerable more risk for GRF asymmetry than during mid-stance.

**Prosthetic and Footwear Considerations**

All subjects in this study either used K2 or K3 prosthetic feet, however specific type of prosthetic was not documented specifically for each individual subject participating in this study. Research conducted by Svoboda et al. found that the type of prosthetic foot has an effect on the variability of GRFs in different planes.\(^{19}\) They found that the solid ankle cushioned heel (SACH) prosthetic foot
has higher variability in the medio-lateral direction where as a Sureflex foot has higher variability in the anterior-posterior direction. Although our research did not show significance in the anterior/posterior plane it should be noted that there was a trend toward significance at initial contact. It is likely that with an increased sample size there would have been significance in this plane as well. It is notable however that this is one of the first studies that has found significant differences in GRFs in the medial lateral plane at terminal stance.

There are also multiple different designs for prosthetic feet and ways that they can be adjusted. Therefore, controlling which type of prosthetic foot was used in this study would have reduced our subject population to an even lower number. Most patients were also not aware of what their K level was or the make and type of their prosthesis, therefore collecting this data was not easily available at the time of data collection. Further research on determining which prosthetics create the greatest GRF symmetry should be considered.

Lastly, footwear and orthotics can contribute to biomechanical and GRF changes during gait. The type of footwear and orthotics used by each subject was not documented and therefore we are unable to make conclusions about the possible effects that they had on our results. Prostheses are designed with the type of footwear the person will be wearing in mind. Controlling for what type of footwear the participants were using would have been too costly and time consuming for our study. Also, because the participants used their normal footwear, changing what type of shoe they were wearing would constitute a threat to the internal validity of the study.
Clinical Relevance

Results from this study support the current literature that persons with unilateral TTAs have gait asymmetries that favor increased weight bearing of the intact limb. Although there was not a direct measure of energy consumption, these results do help to support the literature showing biomechanical loading differences that affect gait efficiency. Understanding these discrepancies between limbs in persons with TTAs can help aid clinicians in how to best address their impairments and improve limb loading and gait efficiency.

GRF data are not readily available to all clinicians, therefore there is a need for detailed literature about GRFs in this population. These results suggest that the most important parts of gait symmetry that should be considered are: medial/lateral and vertical GRFs during initial contact as well as medial/lateral forces during terminal stance. Furthermore, although not statistically significant, there are trends of asymmetries in the anterior/posterior plane during initial contact and the vertical plane during terminal stance. This further suggests that initial contact and terminal stance of the prosthetic limb are the most important factors to improve gait symmetry in persons with TTAs. This can be accomplished through gait training to improve biomechanical causes of gait asymmetries as well as therapeutic exercises to improve the strength discrepancies between limbs.

Limitations

One of the most significant limitations of this study is that the sample size was only 8 subjects. Part of this was because many of the subjects that were scheduled to come in had recent injuries that prevented them from meeting the criteria to take part in data collection. Additionally, the research sessions were 90 minutes and there was no monetary compensation which lead to a decreased incentive to participate. Lastly, because there were rigid exclusion criteria, we lost
subjects that may have been interested but unable because they did not meet the requirements.

Six of the subjects were male and 2 were female leading to possible inherent gender differences that could affect the data. This also created a disproportionate sample of men. This may mean that the results of this study might apply more to males than females.

Because of the nature of recording GRFs, having a more extensive understanding of each type of prosthesis and the way they are adjusted (amount of external/internal rotation) would help to determine if some of the results were due to prosthetic type, fit, or malalignment. Furthermore, information about the time since the subjects’ last prosthetic visit/adjustment was not collected. Therefore, we are unable to say with certainty whether observed GRF abnormalities were due to functional differences or prosthetic recent prosthetic adjustments.

Research suggest that the steps required to reach steady state walking varies depending on multiple factors. In this study, the number of steps allowed before reaching the force plate was 3. This was the maximum number of steps that could be fit on the force platform for most subjects because of its limited size. It has been proposed that it may take anywhere from 3 to 5 steps to reach steady state walking. Therefore, it is possible that not all subjects were able to reach steady state walking prior to making contact with the force plate. It has been noted however that GRF asymmetries and variability do not significantly change when gait velocity is changed.

Even if the subjects did not achieve steady state walking velocity there was an equal number of steps bilaterally until contacting each force plate and this may negate the effects of a diminished gait velocity for analytic purposes. However, it is probable that if the subjects were accelerating when they contacted the
platforms this may have skewed the results of the data, especially in the anterior/posterior plane.

Vertical GRFs increase with increased gait velocity. Statistical significance was not found for the vertical plane during terminal stance in this study although there was a trend towards significance. Consequently, if the subjects did not achieve steady state gait velocity, the vertical GRFs recorded may be artificially lower. If subjects did not achieve steady state gait velocity, perhaps on a longer walkway the results of vertical GRFs would be significant. It is also likely with a greater sample size we would have seen significance in this plane.

Another important factor to distinguish is the difference between persons with traumatic versus dysvascular amputations. This is important for 2 reasons. The first is that the O2 cost for persons with traumatic amputations is significantly less than those with dysvascular amputations. Therefore persons with dysvascular amputations are likely to fatigue sooner, impairing their biomechanics during locomotion. Secondly, dysvascular amputations are typically performed in populations that are less active. Therefore, there may be inherent differences in gait asymmetry between persons with dysvascular and traumatic amputations that are not noted in the literature. Because none of the subjects had amputations due to dysvascular disease, the results of this study may not be as representative of that population.

Additionally, this study lacked a non-amputee control group. This would allow for the comparison of age and weight matched controls to determine the amount of loading differences. This study showed the differences between loading of the intact limb and prosthetic limb, however does not show the relationship between loading of the intact limb in persons with TTA and the limb of persons without TTA. This would allow for comparison with previous studies that have
shown greater peak vertical GRF of the intact limb in persons with TTA versus control. However, there has been extensive research on typical gait and gait asymmetry that demonstrates clearly more significant symmetry than our findings.\textsuperscript{18}

A person’s limb dominance can attribute to more force production as well.\textsuperscript{50}Limb dominance was not collected in this research and is something that if considered, could have been analyzed as well. The subject’s side of amputation varied and the dominant limb prior to amputation was not documented. If the amputated limb had been dominant prior to their surgery, it is possible that it may produce more force than if the non-dominant limb was amputated. Currently, there is not any known literature available on this.

Another limitation to this study was that not all the data collected were analyzed. The original intention of this research was a continuation of a pilot study intending to find comparisons between gluteal muscle activity and ground reaction forces during gait and other functional tasks.\textsuperscript{41}Therefore, the same IRB and protocol were used for the data collection which created lots of extraneous data.

Another consideration is that the age of the subjects ranged from 31 to 67 and that the time since their amputation varied from 1 to 33 years. These significant differences may have affected the results of this study, however, to obtain a viable sample size expanding the inclusion criteria was determined to be of higher priority.

Lastly, the GRF data were not normalized during the analysis of the results. This may have contributed to errors in the examination of the results. Normalization of the GRF data may have affected the results in either direction. For instance, it may have pushed the anterior/posterior forces during loading response into a significant margin or it may have removed the vertical GRF during
loading response to become insignificant. Regardless, it likely would not have changed the results that demonstrated high significance.

**Additional Research**

Further research is required to improve the significance of these results. A bigger sample size would help to improve the threats to external validity in this study. This could be accomplished by reducing the exclusion criteria to allow for persons with minor sores of the stump, if they are not creating discomfort with walking. Also, to get more participants it would be helpful to reduce the amount of collection time. This could be accomplished by removing the data collection of the functional tasks and potentially reducing collection time by 30 minutes. Another way to improve external validity for additional research would be to find more persons with amputations due to dysvascular complications. These data will be more attributable to the projected new population of persons living with LE amputations.

Certain steps should also be taken to prevent threats to internal validity of future studies continuing this research. One way could be to control for steady state walking velocity by comparing walking speed on the force plate walkway to the steady state velocity collected on the Zenomat. Another important step should include collecting more information on the details of the participants’ prostheses (prosthetic type/make, adjustment settings, and the date of most recent adjustments/modifications). Future research analyzing GRFs in this population should consider using biomechanical analysis software to better attribute GRF asymmetries to biomechanical irregularities and better understand the causes of these differences.
For researchers replicating this study, there are a few changes that should be considered. First, the researchers should consider using the Amputee Mobility Predictor to determine subjects K-Scores. This will allow for better comparison of GRFs based on an individual’s level of function and give a better understanding of the variability in this population. Secondly, instead of performing 1 research session to collect all the data, researchers should split up the data collection into 2 sessions. This will allow for 1 session to gather anthropometric and outcome measure data, and a second session to collect EMG and GRF data. The benefits to performing the research in this method are twofold. First, each session will be a shorter amount of time and therefore may be more conducive to prospective subject’s schedules. Second, this will help to eliminate any subject fatigue that may have played a role in GRF variability. Collecting the research with these methods will help strengthen the validity of the results collected.

**Conclusion**

The results of this study confirm there are weight bearing asymmetries in persons with unilateral TTAs. Specific to this population are decreased loading of the prosthetic limb in the medial/lateral and vertical plane during loading response and medial/lateral plane during terminal stance. These asymmetries should be considered by clinicians when developing treatments for this population due to the inherent risks of developing secondary degenerative changes of the intact limb. Special considerations should be made for variables that may be functional adaptations during gait such as shortened step length and decreased terminal stance propulsion. Therapists should focus their attention at improving load bearing tolerance of the prosthetic limb through residual limb strengthening.
Further research should be conducted to incorporate larger sample sizes and reduce validity threats.
REFERENCES
REFERENCES


41. Miller MA. *Abnormal Gluteal Muscle Activity and Ground Reaction Forces Associated With Gait Deviations in Unilateral Transtibial Amputees: A Pilot Study,* California State University, Fresno; 2017.


TABLES
### Table 1. Subject Demographics

<table>
<thead>
<tr>
<th>Scale</th>
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### Table 2. Mean GRF at Loading Response

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**Table 3. Mean GRF at Mid-Stance**

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<td>Fy Residual</td>
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**Table 4. Mean GRF at Terminal Stance**

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**Table 5. T-Test Values**

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<td>Terminal Stance</td>
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Figure 1. Kistler GRF Platform

Figure 2. EMG Wireless System Noraxon
Figure 3. Gluteus Maximum MVIC Testing Position 1

Figure 4. Gluteus Maximus MVIC Testing Position 2
Figure 5. Gluteus Medius MVIC Testing Position 1

Figure 6. Gluteus Medius MVIC Testing Position 2
Figure 7. GRF Loading Response

Figure 8. GRF Mid-Stance
Figure 9. GRF Terminal Stance