Published in final edited form as:

Arch Phys Med Rehabil. 2008 July ; 89(7): 1386–1394. doi:10.1016/j.apmr.2007.10.050.

Differences in Gait Characteristics Between Persons With Bilateral Transtibial Amputations, Due to Peripheral Vascular Disease and Trauma, and Able-Bodied Ambulators

Po-Fu Su, MS, Steven A. Gard, PhD, Robert D. Lipschutz, CP, and Todd A. Kuiken, MD, PhD

Department of Biomedical Engineering, McCormick School of Engineering and Applied Science, Northwestern University, Evanston, IL (Su, Gard, Kuiken); Northwestern University Prosthetics Research Laboratory & Rehabilitation Engineering Research Program, Chicago, IL (Su, Gard); Department of Physical Medicine & Rehabilitation, Feinberg School of Medicine, Northwestern University, Chicago, IL (Gard, Kuiken); Jesse Brown VA Medical Center, Department of Veterans Affairs, Chicago, IL (Gard); Rehabilitation Institute of Chicago, Chicago, IL (Lipschutz, Kuiken); and Northwestern University Prosthetics-Orthotics Center, Chicago, IL (Gard, Lipschutz)

Abstract

Objectives—To examine differences in gait characteristics between persons with bilateral transtibial amputations due to trauma and peripheral vascular disease (PVD); and to compare that with data from able-bodied controls that were previously collected and maintained in a laboratory database.

Design—Observational study of persons with bilateral transtibial amputations.

Setting—A motion analysis laboratory.

Participants—Nineteen bilateral transtibial amputees.

Intervention—No experimental intervention was performed. To standardize the effect of prosthetic foot type, subjects were fitted with Seattle Lightfoot II feet 2 weeks prior to quantitative gait analyses.

Main Outcome Measures—Temporospatial, kinematic, and kinetic gait data were recorded and analyzed.

Results—Results showed that the PVD and trauma subjects' freely selected walking speeds were 0.69m/s and 1.11m/s, respectively, while that of able-bodied control subjects was 1.20m/s. When data were compared on the basis of freely selected walking speed, numerous differences were found in temporospatial, kinematic, and kinetic parameters between the PVD and trauma groups. However, when data from similar speeds were compared, the temporospatial, kinematic, and kinetic gait data demonstrated no statistically significant differences between the 2 amputee groups. Though not statistically significant, the PVD group displayed increased knee ($P=.09$) and

Correspondence to: Po-Fu Su, MS, NUPRL & RERP, 345 E Superior St, RIC 1441, Chicago, IL 60611, p-su@northwestern.edu.

No commercial party having a direct financial interest in the results of the research supporting this article has or will confer a benefit upon the authors or upon any organization with which the authors are associated.

Reprints are not available from the author.

hip ($P=.06$) flexion during swing phase, while the trauma group displayed increased pelvic obliquity ($P=.06$). These actions were believed to represent different strategies to increase swing phase foot clearance. Also, the PVD group exhibited slightly greater hip power ($P=.05$) prior to toe-off.

Conclusions—Many of the differences observed in the quantitative gait data between the trauma and PVD groups appeared to be directly associated with their freely selected walking speed; the trauma group walked at significantly faster freely selected speeds than the PVD group. When their walking speeds were matched, both amputee groups displayed similar gait characteristics, with the exception that they might utilize slightly different strategies to increase foot clearance.

Keywords

Amputees; Biomechanics; Gait; Kinetics; Prostheses and implants; Rehabilitation; Walking

Few studies have directly compared the gait characteristics of persons with unilateral, lower-limb amputation based on etiology, particularly contrasting walking performance in individuals with amputation due to trauma to those with amputation resulting from peripheral vascular disease (PVD).¹⁻⁴ Prosthetists generally prescribe prosthetic components based on considerations of weight, activity level, and the age of the users. However, PVD amputees tend to be older, more sedentary, and are at greater risk for developing serious skin problems on their residual limb(s) compared to traumatic amputees,^{4,5} which may significantly affect the ability of these people to walk.

Persons with unilateral transtibial amputation may employ compensatory actions from their sound limb⁶ when they walk, which can complicate the interpretation of quantitative gait data. Studying the gait of persons with bilateral transtibial amputations eliminates sound limb actions, which will provide a better understanding about how prosthetic componentry and amputation etiology affect ambulation. It is expected that persons with bilateral amputations walk with greater symmetry than unilateral amputees, serving to simplify data analysis and interpretation. Finally, limited data are available in the literature that report gait characteristics of persons with bilateral transtibial amputations,⁷ and no studies have attempted to delineate the effects of amputation etiology in this population. Documenting gait patterns using quantitative data in persons with bilateral amputations is important for establishing realistic expectations for clinicians involved in the treatment and rehabilitation of this small, but significant, population.

Previous studies of persons with unilateral amputations indicate that both standing and walking ability is generally better in persons with traumatic amputations compared with people with amputations resulting from PVD. Barth et al² reported that a trauma group of unilateral transtibial amputees walked at faster freely selected speeds than a PVD group (1.07m/s vs 0.75m/s), and that subjects in the trauma group walked with less energy cost than those in the PVD group. Although the findings in Barth's study were statistically significant, the total number of subjects was small, with only 3 in each group. Standing balance also appears to be affected by amputation etiology. Hermodsson et al¹ separated unilateral transtibial amputee subjects by etiology into PVD and trauma groups and

conducted standing balance tests. They found that the PVD group had greater fore-aft sway than the trauma group, indicating inferior standing balance of the PVD group. These previous studies reported results from persons with unilateral transtibial amputations. The discrepancies between the gait of persons with trauma and PVD amputations is expected to be even greater for people with bilateral amputations.

The purpose of this study was to compare the gait characteristics among persons with bilateral transtibial amputations, specifically among 2 groups having amputation due to either trauma or PVD. Additionally, data from the subjects with amputation were compared with those of able-bodied subjects. We hypothesized that the able-bodied persons would have better walking performance than the trauma group, and that the trauma group would have better gait performance than the PVD group. Specifically, a person with relatively better gait performance will display a faster freely selected walking speed, narrower step width, and reduced peak positive hip powers. Additionally, pelvic rotation was expected to be increased in persons with bilateral transtibial amputations compared with able-bodied subjects because this motion is generally believed to play a more significant role during gait in this population. A pattern of bilateral hip-hiking was also expected for the prosthesis users in order to increase foot clearance during swing phase, which may increase the magnitude of pelvic obliquity compared with the controls.

By examining the walking performance of PVD and trauma subjects, we can develop a better understanding the effect(s) of amputation etiology on their gait and identify additional factors that should be considered when prescribing prostheses and evaluating gait in the clinic. Furthermore, identification of the differences in the gait patterns of PVD and trauma amputees may suggest alternative rehabilitation methods and programs to address the unique needs of these 2 different groups.

METHODS

Participants and Prosthetic Components

Subjects were recruited from clinics and prosthetics fitting centers in the Chicago metropolitan area. Criteria included persons with bilateral transtibial amputations who used prostheses as their primary mode of ambulation who could be classified at a minimum as a Centers for Medicare & Medicaid Services K3 ambulator; were a minimum of 2 years postamputation; were able to walk at least 10 minutes continuously at their freely selected speed; and did not have any known serious health issues such as heart disease. Subjects were not restricted by age, weight, height, or residual limb length. All subjects signed consent forms that were approved by Northwestern University's Institutional Review Board. For comparison, subjects were divided into 2 groups according to the etiology of amputation due to PVD or amputation due to trauma.

At the beginning of the study, an experienced, certified prosthetist fitted all subjects with Seattle Lightfoot II^a feet having appropriate keel stiffness that was selected based on subjects' weight and activity level. Keel selections were made on the basis of Seattle Limb

^aSeattle Systems, 26296 Twelve Trees Ln NW, Poulsbo, WA 98370.

Systems chart that takes into consideration of foot size, weight and activity level of the person being fit, and were not selected based on etiology of amputation. The Seattle Lightfoot II uses a Delrin keel and is a commonly used low profile dynamic response foot. The prostheses that were used in the study were those that had been fitted to individuals by their treating prosthetist. The socket fit was assessed, residual limbs examined and the prosthetic feet were changed by an experienced, certified prosthetist. No major socket adjustments were necessary. When appropriate, the person was referred back to his/her treating prosthetist for any minor adjustments. Modifications to prosthetic alignment were performed dynamically based on visual gait analysis by the prosthetist and feedback from the subject, similar to the procedure routinely performed in the prosthetics clinic.

A quantitative gait analysis was conducted 2 weeks after subjects were fit with the Seattle Lightfoot II feet to permit sufficient accommodation to change in their prostheses. Data that were previously collected from 14 able-bodied persons walking at their freely selected, fast and slow speeds were drawn from a database and used to provide comparisons with the amputee subjects.

Gait Data Acquisition

Data collection and analyses for the study were conducted in the VA Chicago Motion Analysis Research Laboratory (VACMARL). The VACMARL has an 8-camera Eagle Digital RealTime System^b that is used to measure and quantify marker movements. The same modified Helen Hayes marker set⁸ was used to define a biomechanic model in both persons with amputations and able-bodied persons. As the subject walked along the walkway, the positions of the markers were recorded by the motion analysis cameras mounted around the periphery of the room. Six force platforms^c located midway along the walkway and embedded flush with the floor were used to measure ground reaction forces. Both the kinematic and kinetic data were collected using EVaRT software.^b The kinematic data were acquired at 120Hz and the kinetic data were simultaneously recorded at a sampling rate of 960Hz. The ground reaction force and motion data were used to calculate joint moment and power via inverse dynamics using OrthoTrak software.^b

During the gait analysis, subjects were initially instructed to ambulate at their freely selected walking speed, then they walked at their fastest comfortable speed, and finally at their slowest comfortable speed. A total of 10 to 15 trials of data were collected for each walking speed, and the subjects were given the opportunity to rest at any time during the experiment.

Data Analyses

Missing data points in the marker position data were interpolated with a cubic spline technique. The raw marker data were then filtered using a fourth-order bidirectional Butterworth infinite-impulse response digital filter having an effective cutoff frequency of 6.0Hz. OrthoTrak software was used to calculate temporospatial data, joint angles, ground reaction forces, joint moments, and powers. Customized Matlab^d programs were developed

^bMotion Analysis Corp, 3617 Westwind Blvd, Santa Rosa, CA 95403.

^cAdvanced Mechanical Technology Inc, 176 Waltham St, Watertown, MA 02472-4800.

^dThe MathWorks Inc, 3 Apple Hill Dr, Natick, MA 01760-2098.

to calculate means and standard deviations (SDs) for the gait parameters and to generate figures.

Statistical analyses were performed on the speed-matched data of the PVD, trauma, and able-bodied subjects, and also on data from their freely selected speeds. The following parameters were compared between the groups: walking speed, step length, cadence, step width, stance time, double support time, peak-to-peak ankle plantarflexion and dorsiflexion in stance phase, peak-to-peak knee flexion and extension in stance phase, peak-to-peak knee flexion and extension in a gait cycle, peak-to-peak hip flexion and extension, peak-to-peak pelvic rotation in transverse plane, peak-to-peak pelvic obliquity in coronal plane, magnitude of the first peak of the vertical ground reaction force, peak-to-peak fore-aft ground reaction force, peak-to-peak mediolateral (ML) ground reaction force, peak ankle plantarflexion moment, peak ankle dorsiflexion moment, peak ankle power absorption, peak ankle power “generation,” peak hip power absorption, and peak hip power generation. The statistical analyses utilized one-way analysis of variance. SPSS software^e with the Bonferroni correction was used and the level of statistical significance was set at a value of *P* less than .05.

RESULTS

Data were collected from 19 persons with bilateral transtibial amputations and 14 able-bodied subjects (table 1). The PVD group was significantly older than the trauma and the able-bodied groups, and the trauma group was significantly older than the able-bodied group.

Four subjects in the PVD group used a single-point cane on their right side to assist walking during their gait analyses and all other subjects walked without an assistive device. While ambulating, the cane was always held in the subjects’ right hand and was in contact with the ground during the left stance phase. The 4 subjects displayed about 2% decrease in the peak vertical ground reaction force. Therefore, only the right side data from the subjects were analyzed.

Temporospatial Data

The freely selected speed of the PVD group was 0.69m/s, for the trauma group was 1.11m/s, and for the able-bodied group, it was 1.20m/s. Therefore, the PVD and trauma groups walked at 58% and 93%, respectively, of the freely selected speed adopted by the able-bodied controls. At their freely selected speeds, no significant differences were observed between the temporospatial parameters acquired for the trauma and the able-bodied groups. A paired *t* test showed that there was no significant difference between the right and left step lengths for each group of subjects. However, at their freely selected speeds both the trauma and the able-bodied groups displayed significantly longer step lengths, higher cadences, shorter stance times, and shorter double-support times compared with the PVD group (table 2). The PVD group displayed wider step width compared with the able-bodied persons.

^eSPSS Inc, 233 S Wacker Dr, 11th Fl, Chicago, IL 60606.

The walking speeds were comparable between the groups when the PVD group walked at their freely selected speed and the trauma and able-bodied groups walked at their slow speed (see table 2). When statistical analyses were performed at these similar speeds, no statistical differences existed between the 3 groups in their walking speed, step length, cadence, stance time, and double-support time. However, the PVD and trauma groups displayed significantly wider step widths than the able-bodied controls ($P<.001$, $P=.022$, respectively), though there was no difference between the 2 amputee groups.

Gait Kinematics

When walking at their freely selected speeds, the trauma group and the able-bodied subjects displayed significantly greater sagittal plane ankle motion ($P=.023$, $P=.001$, respectively), and stance phase knee flexion ($P<.021$, $P=.003$, respectively), compared with the PVD group (table 3). When data were compared with the groups walking at similar speeds, a larger number of differences in the gait parameters were observed. While the peak-to-peak ankle plantarflexion and dorsiflexion angles in stance phase did not differ significantly between the PVD and trauma groups, they were reduced compared to the able-bodied controls ($P<.001$ for both comparisons) (fig 1, see table 3). The amount of stance phase knee flexion was comparable among all subjects when they walked at similar speeds (fig 2). The PVD group displayed slightly greater swing phase knee flexion compared with the trauma group, but the difference was not significant ($P=.09$) (see table 3). The PVD group exhibited greater hip flexion compared with the trauma group during late swing phase (fig 3), but no significant difference was observed in peak-to-peak hip range of motion between the 2 groups ($P=.06$) (see table 3). The PVD and trauma groups displayed comparable pelvic rotation patterns and magnitudes in the speed-matched comparisons (fig 4), but both amputee groups displayed a nonsignificant trend of increased pelvic rotation compared with the able-bodied subjects (see table 3). The trauma group utilized about 4° more pelvic obliquity (fig 5) than the able-bodied subjects ($P=.025$) and about 3° more than the PVD group ($P=.06$) (see table 3).

Gait Kinetics

When comparing data from the PVD, the trauma, and the able-bodied groups walking at their freely selected speeds, the PVD group displayed a smaller first peak of vertical ground reaction force compared with the trauma group ($P=.047$) (table 4). The PVD group exhibited smaller peak-to-peak fore-aft ground reaction force compared with the trauma and able-bodied subjects ($P<.001$ for both comparisons). The posteriorly directed portion of the fore-aft ground reaction force is sometimes described as the “braking” force, associated with the forward deceleration of the body center of mass; the anteriorly directed portion is referred to as the “propulsive” force and is associated with the forward acceleration of the body center of mass. The peak-to-peak ML ground reaction force did not differ significantly between the 3 groups. Both the PVD and trauma groups displayed smaller peak ankle plantarflexion moments compared to the able-bodied subjects ($P<.001$ for both comparisons). The trauma group demonstrated a greater ankle dorsiflexion moment compared with the able-bodied subjects ($P=.007$). Finally, the PVD and trauma groups displayed smaller peak ankle positive power compared with the able-bodied subjects ($P<.001$, $P=.001$, respectively).

When the groups walked at comparable speeds, the vertical ground reaction force curves were similar. The PVD and trauma groups displayed similar peak-to-peak fore-aft ground reaction forces (see table 4), but they were significantly smaller than those of the able-bodied subjects ($P=.001$, $P=.006$, respectively) (fig 6). The peak-to-peak ML ground reaction force did not differ significantly between the 3 groups. The ankle moment and power curves of the PVD and trauma groups were similar and their peak magnitudes were not significantly different (figs 7, 8). While the PVD and trauma groups showed comparable negative hip joint powers (fig 9), at approximately the time of toe-off the PVD group displayed greater positive hip joint powers compared with the trauma group ($P=.054$) (see table 4), though the difference was not statistically significant. Compared with able-bodied subjects, the PVD and trauma groups displayed smaller peak ankle plantarflexion moments, greater peak ankle dorsiflexion moments, and smaller peak positive ankle powers.

DISCUSSION

The freely selected walking speed can be used as an indicator of overall walking performance in persons with gait pathology.^{9,10} The results supported the hypothesis of the study and showed that the trauma group generally walked at faster self-selected speeds than the PVD group, and both the trauma and PVD groups walked slower than the able-bodied persons. The result was consistent with gait analysis data of persons with unilateral transtibial amputation.^{1,2} The trauma group may have better walking ability than the PVD group because they were younger and more active. The prosthetic needs for faster ambulators are likely to be different from those who walk slower.

The results showed that all of the subjects, including the 4 who used canes, demonstrated reasonably good symmetry during gait, and similar vertical ground reaction force magnitudes were observed for both legs. Therefore, those 4 subjects who walked with a cane probably used it to provide a sense of security, to improve stability and to prevent falling rather than to support a significant amount of body weight during walking. Although the use of the cane affected their kinetic measurements on the left, it should have limited effect on the kinematic and kinetic measurements on the right side.

When data were compared with the groups walking at their freely selected speeds, a number of statistically significant differences were found in temporospatial, kinematic, and kinetic gait parameters. These analyses were performed because the characteristics demonstrated by the amputee subjects walking at their freely selected speeds are those typically observed in the clinic and were therefore of interest. However, the freely selected walking speeds were considerably different between groups: the PVD group walked at 0.69m/s, the trauma group walked at 1.11m/s, and the able-bodied control group walked at 1.20m/s. While the freely selected speed of the PVD group was significantly different from those of the trauma and able-bodied group, the speed of the trauma group and of the able-bodied group were not determined to be significantly different. All of the gait parameters that were measured and analyzed are known to vary with walking speed. Based on the analysis of data acquired at the 3 groups' freely selected speeds, it is not known if the observed differences are due to the etiology of amputation, if they represent a difference in gait strategies adopted by the different groups, or if they are merely due to the known difference in walking speed.

Therefore, we feel that comparisons of this type are prone to error in both analysis and interpretation if walking speed is not taken into account. We recommend that whenever possible the walking speeds between different groups be matched, or at least similar, prior to performing statistical analyses.

Analysis of the data at similar walking speeds between the groups eliminated many of the differences between the gait parameters of interest, allowing for more appropriate comparisons between the PVD, the trauma, and able-bodied subjects. None of the temporospatial parameters was significantly different when the walking speeds were matched between the PVD and trauma groups. However, the PVD group was observed to walk with about a 20% wider base of support compared to the trauma group (see table 2). Persons with inferior dynamic balance generally walk with greater lateral trunk motion and adopt an increased step width to enhance stability.¹¹ A wider base of support in the PVD group indicates that their balance may have been compromised, possibly attributable to poor sensation and proprioception, or perhaps their perception of stability. Furthermore, all subjects with bilateral transtibial amputations were observed to walk with a wider base of support compared with able-bodied individuals. These results are consistent with those from another study that investigated standing balance in persons with unilateral transtibial amputation.¹² The PVD group in that study had significant greater fore-aft sway compared to the trauma group, again indicating that the PVD subjects had inferior balance.

Generally, the PVD and trauma subject groups exhibited similar kinematic patterns. Both groups showed similar ankle motions during gait (see fig 1), and in both groups the peak ankle dorsiflexion and plantarflexion angles were smaller in comparison to the able-bodied subjects. The Seattle Lightfoot II foot does not have an articulating ankle joint, so the measured ankle joint plantarflexion motion during early stance phase was primarily due to the compression of the heel, while the dorsiflexion motion during mid to late stance resulted from the bending of the keel of the prosthetic foot. Both groups displayed comparable knee and hip motion during stance phase, but the PVD group showed increased knee and hip flexion during swing phase (see figs 2, 3). The differences in increased knee and hip flexion peaks did not exceed the significant level of .05. Nonetheless, these increased joint rotations may have compensated for their poor proprioception and assisted the PVD subjects in toe clearance by lifting the foot higher above the ground.

Both amputee groups displayed a trend of greater pelvic rotation than the able-bodied controls (see table 3, fig 4). In the clinic, one of the most noticeable gait pathologies in bilateral amputees is that their feet often rotate on the floor as they walk. This is presumed to be due to increased pelvic rotation combined with the loss of ability to counter rotate at the ankle or compensate with the sound leg. The data presented in this study are consistent with this proposition, since pelvic rotation was considerably greater in the bilateral amputees. The result may suggest that tibial rotators should be considered for this patient population to absorb the transverse plane torque induced in the prosthesis and thereby alleviate some of the shear stress acting between the shoe sole and the ground, and between the prosthetic socket and the user's residual limb. Further research is also needed to optimize tibial rotator compliance and design for bilateral transtibial amputees.

Contrary to the hypothesis that a better ambulator will walk with reduced pelvic obliquity, the trauma group exhibited greater pelvic obliquity than the PVD group (see table 3, fig 5). Excessive pelvic obliquity during mid-swing—a compensatory action known as “hip hiking”—has been documented in both bilateral and unilateral transtibial amputees¹³ as a means of increasing toe clearance. (Note that hip hiking during mid-swing for one side of the body will also be reflected in the pelvic obliquity data during midstance on the contralateral side of the body.) Our kinematic results indicate that PVD and trauma subjects may adopt different compensatory strategies to increase toe clearance during swing phase. Apparently, the PVD group used greater knee and hip motions to increase swing leg toe clearance, while the trauma group relied on increased pelvic obliquity (ie, hip hiking). These differences in PVD and trauma amputee gait may be helpful for performing prosthetic dynamic alignment and suggest different strategies be considered for rehabilitation programs. Traumatic amputees are likely more prone to excess hip hiking, which decreases efficiency of gait and could also lead to hip and back pathology. The rehabilitation team should carefully monitor pelvic obliquity and train the patient to limit excessive hip hike with increased knee flexion.

Kinetic parameters were similar for both PVD and trauma groups when walking speeds were matched. Subjects displayed comparable vertical ground reaction force, fore-aft ground reaction force, ankle moments, and ankle powers (see figs 7, 8). It is important to note that the prosthetic foot is passive and cannot generate any power. Therefore, the ankle joint “power” of the prosthesis presumably indicates the amount of the energy stored and returned by the deformation of the prosthetic foot. Compared with able-bodied subjects, the PVD and trauma groups displayed reduced fore-aft ground reaction force, peak ankle plantarflexor moment, peak positive ankle power when the walking speed is matched. Able-bodied individuals actively plantarflex at the end of stance phase, which is believed to provide push-off and generate significant power for forward progression. The absence of the ankle plantarflexors in the PVD and trauma groups may have contributed to the reduced fore-aft ground reaction force, peak ankle plantarflexor moment, and ankle power “generation” (ie, energy return) that was observed. The hip joint powers were highly variable among all the subjects (see fig 9). The PVD group displayed a trend of greater positive hip joint powers near toe-off than the trauma group (see table 4). Subjects in the PVD group may have adopted increased hip joint powers to boost acceleration of the leg during pre-swing with the intent of achieving greater hip flexion during mid-swing (see figs 3, 9). The PVD group data demonstrated double peaks in their hip power near toe-off while the trauma group and able-bodied individuals showed only a single peak. However, only 1 person in the PVD group actually displayed the double peaks hip powers around toe-off. The double-peaks in the mean hip power curve were primarily a consequence of averaging waveforms with different peak timings among the individual subjects.

Clinical Implications

Many of the differences observed in the quantitative gait data between the trauma and PVD groups appeared to be directly associated with their freely selected walking speed, which define the gait characteristics typically observed when the patient comes to the clinic. When their walking speeds were matched, both amputee groups displayed similar gait

characteristics. Nonetheless, consideration for the clinical presentation is an important consideration for evaluation of rehabilitation potential. The magnitudes of hip power, walking speed and pelvic rotation are three factors that may influence the prosthetist in his/her decision-making regarding alignment changes and/or component selection. Prosthetists will often attempt to normalize the gait of an amputee when a gait deviation exists. If studies such as this one indicate that a well-defined patient population consistently displays a particular gait deviation, the prosthetist may learn to initially accept that deviation as “the norm.” Additional therapy and/or research should focus on determining methods of resolving these deviations and increasing gait efficiency. The expectation for rehabilitation potential of some groups of amputees may be either over- or underestimated if little is known about their gait characteristics and other factors related to their general well-being. This is a particularly difficult issue to resolve, and is part of the reason why the characteristics of gait among reasonably well-defined groups of prosthesis users should be examined and documented. We need to develop prosthetic components with improved function that will enhance the user’s ability to ambulate with decreased gait deviations, at higher walking speeds and with increased efficiency. These components may indeed need to be specific to etiology and/or amputation level.

Study Limitations

There were several limitations to our investigation. First, subjects in the amputee groups were not age-matched. Amputation due to PVD is more likely to occur later in life, which explains why subjects in the PVD group were considerably older than those in the trauma group. Therefore, some of the gait differences that were observed between the PVD and trauma groups may have been related to their age difference, specifically to the fact that some older individuals will walk at slower speeds than younger ones. The speed-matched comparisons we performed were intended to eliminate differences that were attributable to variations in walking speed alone. Also, the results showed that several comparisons between the PVD and trauma groups were close to the statistically significant level of .05, but were not significantly different. A greater number of subjects in the study would have increased the study power and consequently, either support the observed trends or reject them. Finally, the link segment model that was used for inverse dynamic calculations of joint moments and powers did not take each subject’s prosthesis mass and moment of inertia into account. It is generally known that the mass of the prosthesis, the location of the segmental center of mass, and the limb segment’s moment of inertia will be different between the prosthesis users and the able-bodied controls. Because the linear and angular accelerations of the prosthesis are low during stance phase, we do not expect these differences to significantly affect our results. During swing phase, however, there could be differences in the moments and powers calculated for the hip and knee joints of the amputee subjects. For this reason, the swing phase moments and powers were not emphasized in the presentation of results. Nonetheless, whenever possible and feasible the unique anthropometric measures from subjects should be incorporated into biomechanic models to improve accuracy of calculated measures.

CONCLUSIONS

Many of the differences observed in the quantitative gait data between the trauma and PVD groups appeared to be directly associated with their freely selected walking speed. Specifically, the trauma group walked at significantly faster freely selected speeds than the PVD group. When their walking speeds were matched, both amputee groups displayed similar gait characteristics, with the exception that they appeared to utilize slightly different strategies to increase swing phase foot clearance. The PVD group displayed increased knee and hip flexion during swing phase, while the trauma group displayed increased pelvic obliquity (ie, hip hiking). The PVD group also exhibited a greater hip power prior to toe-off.

Acknowledgments

Supported by the National Institute of Child Health and Human Development, the National Institutes of Health (grant no.1R01HD42592).

The contents of this study are solely the responsibility of the authors and do not necessarily represent the official views of the National Institute of Child Health and Human Development. Data for this project were acquired in the VA Chicago Motion Analysis Research Laboratory of the Jesse Brown VA Medical Center, Chicago, IL. We gratefully acknowledge the kind review and suggestions of R.J. Garrick, PhD.

References

1. Hermodsson Y, Ekdahl C, Persson BM, et al. Gait in male trans-tibial amputees: a comparative study with healthy subjects in relation to walking speed. *Prosthet Orthot Int*. 1994; 18:68–77. [PubMed: 7991363]
2. Barth DG, Schumacher L, Sienko-Thomas S. Gait analysis and energy cost of below-knee amputees wearing six different prosthetic feet. *J Prosthet Orthot*. 1992; 4:63–75.
3. Torburn L, Powers CM, Guitierrez R, Perry J. Energy expenditure during ambulation in dysvascular and traumatic below-knee amputees: a comparison of five prosthetic feet. *J Rehabil Res Dev*. 1995; 32:111–9. [PubMed: 7562650]
4. Hubbard WA, McElroy GK. Benchmark data for elderly, vascular trans-tibial amputees after rehabilitation. *Prosthet Orthot Int*. 1994; 18:142–9. [PubMed: 7724347]
5. Carrington AL, Abbott CA, Griffiths J, et al. Peripheral vascular and nerve function associated with lower limb amputation in people with and without diabetes. *Clin Sci (Lond)*. 2001; 101:261. [PubMed: 11524043]
6. Winter DA, Sienko SE. Biomechanics of below-knee amputee gait. *J Biomech*. 1988; 21:361–7. [PubMed: 3417688]
7. Su P, Gard SA, Lipschutz RD, Kuiken TA. Gait characteristics of persons with bilateral transtibial amputations. *J Rehabil Res Dev*. 2007; 44:491–502. [PubMed: 18247246]
8. Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. *J Orthop Res*. 1990; 8:383–92. [PubMed: 2324857]
9. Andriacchi TP, Ogle JA, Galante JO. Walking speed as a basis for normal and abnormal gait measurements. *J Biomech*. 1977; 10:261–8. [PubMed: 858732]
10. Boonstra AM, Fidler V, Eisma WH. Walking speed of normal subjects and amputees: aspects of validity of gait analysis. *Prosthet Orthot Int*. 1993; 17:78–82. [PubMed: 8233772]
11. Murray MP, Sepic SB, Gardner GM, Mollinger LA. Gait patterns of above-knee amputees using constant friction knee components. *Bull Prosthet Res*. 1980; 17:35–45. [PubMed: 7260459]
12. Hermodsson Y, Ekdahl C, Persson BM, Roxendal G. Standing balance in trans-tibial amputees following vascular disease or trauma: a comparative study with healthy subjects. *Prosthet Orthot Int*. 1994; 18:150–8. [PubMed: 7724348]

13. Michaud SB, Gard SA, Childress DS. A preliminary investigation of pelvic obliquity patterns during gait in persons with transtibial and transfemoral amputation. *J Rehabil Res Dev.* 2000; 37:1–10. [PubMed: 10847567]

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Figure 1.

Plot showing the speed-matched mean patterns of sagittal plane ankle joint angles for the PVD and trauma (TRA) amputee groups walking at about 0.7m/s and able-bodied (AB) persons walking at 0.82m/s. The standard deviations of the two groups were comparable; the shaded area on either side of the mean indicates one standard deviation of the TRA group amputees. The vertical line represents toe-off.

Figure 2.

The speed-matched mean patterns of sagittal plane knee joint angles. Abbreviations: AB, able-bodied; TRA, trauma.

Figure 3.
Plot showing the speed-matched mean patterns of sagittal plane hip joint angles.
Abbreviations: AB, able-bodied; TRA, trauma.

Figure 4. The speed-matched mean patterns of pelvic rotation angles. Abbreviations: AB, able-bodied; TRA, trauma.

Figure 5. The speed-matched mean patterns of pelvic obliquity angles. Abbreviations: AB, able-bodied; TRA, trauma.

Figure 6.

The speed-matched mean patterns of fore-aft ground reaction forces (GRFs). Abbreviations: AB, able-bodied; BW, body weight; TRA, trauma.

Figure 7.
The speed-matched mean patterns of ankle flexion and extension movements.
Abbreviations: AB, able-bodied; TRA, trauma.

Figure 8.

The speed-matched mean patterns of ankle powers. Abbreviations: AB, able-bodied; TRA, trauma.

Figure 9. The speed-matched mean patterns of hip powers. Abbreviations: AB, able-bodied; TRA, trauma.

Table 1

Subject's Vital Statistics

Subject	Age (y)	Sex	Height (cm)	Mass (kg)
Trauma group				
1	22	Female	168	53
2	23	Male	193	99
3	47	Female	167	65
4	52	Male	172	87
5	63	Male	175	89
6	67	Male	177	92
7	50	Male	176	76
8	30	Male	170	51
9	31	Male	168	97
10	43	Female	165	78
Mean	42.8		173.0	78.7
SD	15.9		8.2	17.4
PVD group				
1	51	Male	172	62
2	83	Male	169	76
3	78	Male	172	93
4	58	Male	168	68
5	50	Male	175	80
6	76	Female	163	61
7	60	Male	186	91
8	59	Male	174	93
9	61	Female	159	60
Mean	64.0		170.8	76.0
SD	12.0		7.7	14.0
Able-bodied group*				
Mean	25.6		174.2	72.3
SD	2.6		9.9	12.1

* The able-bodied data were obtained from the laboratory database.

Table 2

Temporal-Spatial Data

Temporal-spatial data													
			PVD (1)			TRA (2)			AB (3)			Significance	
			Slow	Freely-selected	Fast	Slow	Freely-selected	Fast	Slow	Freely-selected	Fast	Freely-selected	Matched
			0.45	0.69	0.88	0.70	1.11	1.42	0.82	1.21	1.82	1-2, 1-3	
	Walking speed (m/s)		39.3	49.1	55.6	50.8	63.9	72.7	58.2	69.1	84.4	1-2, 1-3	
	Step length (cm)		66.1	83.9	94.7	82	103.7	117.6	84.3	104.3	129.5	1-2, 1-3	
	Cadence (step/min)		21.3	20.7	19.5	17.6	16.8	16.6	12.2	11.6	13.6	1-3	1-3, 2-3
	Step width (cm)		72.1	67.1	65.6	68.8	63.7	60.4	65.2	61.7	60.2	1-2, 1-3	
	Stance time (% gait cycle)		22.4	17	15.5	16.3	12.2	10.4	15.1	11.5	9.8	1-2, 1-3	
	Double support time (% gait cycle)												

PVD (1) = peripheral vascular diseases subjects, group 1; TRA (2) = trauma subjects, group 2; AB = Able-bodied subjects, group 3. “Normal” and “Matched” in Significance section indicate significant differences for freely-selected (i.e., normal) walking speed comparisons and matched walking speed comparisons (shaded). “1-2”, “1-3” and “2-3” are used to indicate that the differences in the gait parameter between the respective groups were significant. There is no p-value between 0.1 and 0.05.

Table 3

Kinematic Data

	Kinematic data										
	PVD (1)			TRA (2)			AB (3)			Significance	
	Slow	Freely-selected	Fast	Slow	Freely-selected	Fast	Slow	Freely-selected	Fast	Freely-selected	Matched
P-P ankle plantarflexion/dorsi flexion in stance phase	9.1	11.0	12.1	11.4	14.0	15.8	20.2	19.5	21.2	1-3, 2-3	1-3, 2-3
P-P knee flexion/extension in stance phase	10.3	11.7	13.7	10.4	13.1	15.9	16.1	22.2	23.2	1-3, 2-3	
P-P knee flexion/extension in a gait cycle	61.7	66.1	69.7	55.6	63.8	68.2	61.7	67.7	68.4		1-2*
P-P hip flexion/extension	39.9	43.9	46.5	37.9	43.4	49.1	36.5	43.1	49.7		1-2*
P-P pelvic rotation in transverse plane	12.7	11.4	10.4	12.2	12.3	14.6	9.5	7.4	11.3		
P-P pelvic obliquity in coronal plane	8.7	7.4	6.7	9.9	9.2	10.7	6.3	8.2	14.3		1-2*, 2-3

The unit for all the measurements is degrees. PVD (1) = peripheral vascular diseases subjects, group 1; TRA (2) = trauma subjects, group 2; AB = Able-bodied subjects, group 3. "Normal" and "Matched" in Significance section indicate significant differences for freely-selected (i.e., normal) walking speed comparisons and matched walking speed comparisons (shaded) respectively. "1,2", "1,3" and "2,3" are used to indicate that the differences in the gait parameter between the respective groups were significant.

* indicates the result is not statistically significant but $0.10 > p > 0.05$.

Table 4

Kinetic Data

	Kinetic data										
	PVD (1)			TRA (2)			AB (3)			Significance	
	Slow	Freely-selected	Fast	Slow	Freely-selected	Fast	Slow	Freely-selected	Fast	Freely-selected	Matched
First peak vertical GRF (BW)	1.04	1.06	1.10	1.06	1.15	1.32	1.05	1.12	1.33	1-2	
Peak-to-peak fore-aft GRF (BW)	0.12	0.16	0.21	0.17	0.29	0.41	0.24	0.39	0.55	1-2, 1-3	1-3, 2-3
Peak ankle plantarflexion moment (Nm/kg)	1.01	1.08	1.14	1.04	1.14	1.23	1.28	1.39	1.62	1-3, 2-3	1-3, 2-3
Peak ankle dorsiflexion moment (Nm/kg)	0.14	0.17	0.20	0.15	0.21	0.26	0.10	0.15	0.15	2-3	1-3, 2-3
Peak positive ankle power (watt/kg)	0.16	0.25	0.33	0.27	0.50	0.73	1.26	2.37	3.73		
Peak negative ankle power (watt/kg)	0.46	0.72	0.89	0.53	0.88	1.38	0.71	0.87	0.97	1-3, 2-3	1-3, 2-3
Peak positive hip power (watt/kg)	0.48	0.71	1.11	0.50	1.18	1.98	0.50	1.19	1.18		
Peak negative hip power (watt/kg)	0.18	0.26	0.41	0.23	0.55	1.04	0.23	0.54	2.13		

PVD (1) = peripheral vascular diseases subjects, group 1; TRA (2) = trauma subjects, group 2; AB = Able-bodied subjects, group 3. "Normal" and "Matched" in Significance section indicate significant differences for freely-selected (i.e., normal) walking speed comparisons and matched walking speed comparisons (shaded) respectively. "1-2", "1-3" and "2-3" are used to indicate that the differences in the gait parameter between the respective groups were significant. There is no p-value between 0.1 and 0.05.