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Effects of diabetic peripheral neuropathy on gait in vascular trans-tibial amputees

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ABSTRACT

Background: Patients with diabetes often develop diabetic peripheral neuropathy, which is a distal symmetric polyneuropathy, so foot function on the non-amputated side is expected to affect gait in vascular trans-tibial amputees. However, there is little information on the kinematics and kinetics of gait or the effects of diabetic peripheral neuropathy in vascular trans-tibial amputees. This study aimed to clarify these effects, including the biomechanics of the ankle on the non-amputated side.

Methods: Participants were 10 vascular trans-tibial amputees with diabetic peripheral neuropathy (group V) and 8 traumatic trans-tibial amputees (group T). Each subject's gait was analyzed at a self-selected speed using a three-dimensional motion analyzer and force plates.

Findings: Ankle plantarflexion angle, heel elevation angle, and peak and impulse of anterior ground reaction force were smaller on the non-amputated side during pre-swing in group V than in group T. Center of gravity during pre-swing on the non-amputated side was lower in group V than in group T. Hip extension torque during loading response on the prosthetic side was greater in group V than in group T.

Interpretation: These findings suggest that the biomechanical function of the ankle on the non-amputated side during pre-swing is poorer in vascular trans-tibial amputees with DPN than in traumatic trans-tibial amputees; the height of the center of gravity could not be maintained during this phase in vascular trans-tibial amputees with diabetic peripheral neuropathy. The hip joint on the prosthetic side compensated for this diminished function at the ankle during loading response.

1. Introduction

The World Health Organization (WHO) reported an increase in the number of persons with diabetes worldwide from 180 million in 1980 to 420 million in 2014 (WHO, 2014). Patients with diabetes often develop diabetic peripheral neuropathy (DPN), which manifests as spontaneous pain, numbness, and hypesthesia in the extremities (Boulton et al., 2005). The prevalence of DPN among diabetic patients is generally reported to be about 20% (Adler et al., 1997; Partanen et al., 1995; Tesfaye et al., 2005). In Japan, DPN has been reported to occur in 43.7% of patients with an approximately 10-year history of diabetes (Japan Promotion Council for Diabetes Prevention and Countermeasures, 2010). DPN also increases the risk of diabetic foot lesions (infections, ulcers, destructive deep tissue lesions), and 7–20% of patients with DPN reportedly undergo lower limb amputation (Frykberg et al., 2006). The number of vascular lower leg amputations is increasing, with a shift in the indication from traumatic to vascular because of the increasing incidence of diabetic foot lesions (Fletcher et al., 2001; Stone et al., 2006; The Global Lower Extremity Amputation Study Group, 2000).

DPN tends to be a distal symmetric polyneuropathy, so many vascular lower leg amputees also have problems in the non-amputated foot. Gait speed is slower and oxygen consumption is higher in vascular trans-tibial amputees than in traumatic trans-tibial amputees (Waters et al., 1976); also, the double support phases are prolonged and step length is shortened (Parker et al., 2013). However, problems in the limbs bilaterally might have affected the kinetic and kinematic findings in previous studies, and the effect of DPN on the biomechanical function of the ankle in the non-amputated limb has not been investigated.

Vertical and anterior ground reaction forces (GRFs) in late stance phase have been reported to be small in diabetic patients with DPN (Katoulis et al., 1997; Mueller et al., 1994; Raspovic, 2013; Savelberg et al., 2009; Uccioli et al., 2001; Yavuzer et al., 2006). Small ankle plantarflexion torque has also been reported to affect heel-off by

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shortening step length and slowing gait speed (Brown et al., 2014; Katoulis et al., 1997; Mueller et al., 1994; Petrovic et al., 2017; Rao et al., 2006, 2010). These observations suggest that problems might also occur on the non-amputated side. Generally, because the prosthetic foot is less mobile in the direction of ankle plantarflexion, there is less propulsion in late stance phase than on the non-amputated side, even in patients with an energy-storage-and-return prosthesis (Gates et al., 2013; Silverman et al., 2008; Ventura et al., 2011a, 2011b; Zmitrewicz et al., 2007). Ventura et al. (2011a) reported that the height of the center of gravity (CoG) during late stance phase of the prosthetic limb depends on the characteristics of the prosthetic foot, but is lower than that of the non-amputated side. Loading response on the non-amputated side occurs at the same time as pre-swing on the amputated side, and the torque and power produced by extension of the hip joint during loading response have been found to be greater on the non-amputated side in amputees than in non-amputees (Bateni and Olney, 2002; Grumillier et al., 2008). The above-mentioned reports suggest that the weakness of push-off by the prosthetic foot during pre-swing is compensated for by the hip joint during loading response on the non-amputated side.

It has been suggested that vascular trans-tibial amputees with DPN have weak propulsive force in late stance phase, not only in the prosthetic foot but also in the contralateral foot because diabetic patients with DPN generate less propulsive force (Katoulis et al., 1997; Mueller et al., 1994; Savelberg et al., 2009; Uccioli et al., 2001).

Hence, as reported by Waters et al. (1976), compared with traumatic trans-tibial amputees, vascular trans-tibial amputees with DPN have reduced walking performance and decreased ability to shift their CoG upwards in late stance phase on the non-amputated side, which might be compensated for by the hip joint on the prosthetic side in early stance phase. To our knowledge, no previous study has investigated the compensatory mechanism by which the ankle joint raises the CoG on either the amputated side or non-amputated side.

This study sought to compare the gait pattern in vascular trans-tibial amputees with DPN with that in traumatic trans-tibial amputees and to identify the differences in kinetics and kinematics between the amputated and non-amputated limbs. We generated the following three hypotheses to explain these differences between these two groups of amputees: 1) propulsion is weaker on the non-amputated side in late stance phase; 2) low propulsion in late stance phase on the non-amputated side influences the height of the CoG; and 3) the hip on the prosthetic side compensates for the weak propulsion in late stance phase on the non-amputated side.

2. Methods

2.1. Subjects

Eighteen community-dwelling patients who had been documented as having had a prosthetic gait for at least 1 year were enrolled in the study (Table 1). Ten of these patients had undergone unilateral vascular trans-tibial amputation for diabetic gangrene (prosthetic side) and had DPN on the contralateral (non-amputated) side (designated the V-TTA with DPN group). Eight age-matched traumatic trans-tibial amputees (designated the T-TTA group) served as controls. DPN was diagnosed according to the American Diabetic Association criteria (Tesfaye et al., 2010). Subjects in the V-TTA with DPN group were required to meet at least two of the following criteria for DPN: 1) neurologic symptoms in the lower extremities; 2) decreased sensation in the distal lower extremities; and 3) attenuation/loss of the Achilles tendon reflex. Eligibility criteria common to both groups were 1) use of a lower leg prosthesis in activities of daily living and ability to walk without an aid; 2) a standard stump with a length that was 20–50% that of the tibia; and 3) use of a total surface bearing prosthesis. Exclusion criteria were 1) orthopedic or neuromuscular disease other than amputation; 2) peripheral neuropathy other than DPN; 3) wound or pain in the stump; 4) Fontaine stage II or worse intermittent claudication; and 5) ulcer or callosity on the non-amputated foot. To account for the variability in the components of a prosthetic foot, the study participants were recruited such that the setting of the prosthetic limb on the amputated side was comparable between the two groups.

Table 1
Patient characteristics at baseline.

	VTA with DPN (n = 10)	TTA (n = 8)	p-Value
Sex (M/F)	7/3	7/1	
Age (years)	62 (53–74)	60 (50–84)	NS
Weight (cm)	166 (150–185)	166 (148–178)	NS
BMI (kg/m^2)	27 (20–28)	24 (20 – 31)	NS
Stump length (cm)	14 (10 – 20)	15 (11 – 20)	NS
Foot prosthesis used	SACH: 1		
	Uniaxial: 1	Uniaxial: 1	
	Energy-storage: 8	Energy-storage: 7	

Data are shown as the median and range. BMI, body mass index; DPN, diabetic peripheral neuropathy; NS, not statistically significant; TTA, traumatic trans-tibial amputation; VTA, vascular trans-tibial amputation.

2.2. Experimental protocol

Measurements were recorded at two separate laboratories, one at the International University of Health and Welfare, Mita Hospital, and the other at Ibaraki Prefectural University of Health Sciences. The laboratory at Mita Hospital has a synchronized three-dimensional motion analysis system comprising a three-dimensional motion analyzer (Vicon MX, Vicon Motion Systems, Oxford, UK), 6 force plates (AMTI, Watertown, MA, USA) and 10 infrared cameras. The laboratory at Ibaraki Prefectural University of Health Sciences has a Vicon MX motion analyzer, 4 force plates (Kistler, Winterthur, Switzerland) and 8 infrared cameras. Sampling frequency was 100 Hz for the infrared cameras and force plates. Before recording the lower leg measurements in the amputees, measurements were recorded in healthy non-amputees in both laboratories to confirm that the data were obtained with satisfactory inter-laboratory consistency.

34 Reflective markers (14 mm in diameter) were attached to create three-dimensional body segments according to the Helen Hayes Hospital Marker Set (Kadaba et al., 1990). Markers were attached at the same height on the knee of the amputated leg and the foot portion of the prosthesis as on the non-amputated side. The second metatarsal is used as the toe point in the Helen Hayes Hospital Marker Set but is difficult to identify in the prosthetic foot, so the mid-point of the two markers was used on both feet. Shoes were worn during the measurements, so markers on the foot were attached to the surface of each shoe.

Measurements were taken while each subject was walking at a self-selected speed to ensure recording of a representative gait. All subjects wore the prostheses they were accustomed to without standardization. GRF was measured first during static standing on the force plates and subjects were allowed to use either limb first to initiate walking. Each subject performed more than 10 trials to ensure that there were 5 trials for the non-amputated side and 5 trials for the side with the prosthetic limb.

2.3. Data processing

Data obtained by the infrared cameras and by the force plates were processed using low-pass (fourth-order reclusive Butterworth) filters at 6 Hz and 18 Hz, respectively, using the Vicon Nexus software (version 1.7.1, Vicon Motion Systems). Kinematic and kinetic parameters were then calculated using Vicon Body Builder software (version 3.6.1, Vicon Motion Systems). Spatial and temporal parameters were calculated using the Vicon Work Station (Vicon Motion Systems). Kinematic and kinetic parameters were calculated from values obtained by the force