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Increased minimum toe clearance variability in patients with peripheral arterial disease

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ABSTRACT

Individuals with peripheral arterial disease (PAD) report difficulty walking and experience 73% more falls than their healthy counterparts, but no studies have investigated functional mechanisms contributing to increased falls. Minimum toe clearance (MTC) is the minimum vertical distance between the toe of the swinging leg and the walking surface when the leg is swinging, and decreased values are associated with an increased risk for falls. This study is the first such analysis in patients with PAD. Eighteen individuals with PAD and eighteen healthy controls walked on a treadmill before and after the onset of claudication pain. Mean MTC and the standard deviation of MTC values across the trial were calculated. Mean MTC was not different between groups in the pain-free ($P = 0.244$) or pain conditions ($P = 0.565$). MTC variability was increased for patients with PAD in pain-free ($P = 0.048$) and pain conditions ($P = 0.019$). No significant differences existed between conditions for MTC mean ($P = 0.134$) or MTC variability ($P = 0.123$). Increased MTC variability is present before and after the onset of claudication pain, and may be a useful assessment for treatment and rehabilitation efficacy in these patients.

Introduction

The most common symptom of peripheral arterial disease (PAD) is intermittent claudication [1], which is characterized by a cramping type of muscle pain in the lower extremities brought on by physical activity and relieved with rest. As 12–20% of all individuals 60 years of age and older [2] are afflicted with PAD, and falls are a primary source of injury and death among the elderly, falls are an additional concern in this patient population. Not surprisingly, reports estimate that individuals with PAD experience 73% more falls than their healthy counterparts along with a greater prevalence of ambulatory stumbling and overall unsteadiness [3]. However, there has been little investigation into what is contributing to this increased rate of falling in patients with PAD.

There are many possible mechanisms related to physical function to explain the stumbling and unsteadiness in patients with PAD. Many of these mechanisms have come as the result of recent studies using advanced biomechanics analyses that have revealed differences in kinematic and kinetic measures between patients with PAD and healthy controls [4–10]. During the stance phase of walking, patients exhibit a completely different joint power profile when compared to healthy controls. This includes reduced power absorption at the knee in early stance and reduced power generation at the ankle during late stance [6,10]. Patients with PAD also have decreased step length, cadence, and walking speed [4,11], which can contribute to unsteadiness [12]. Another characteristic of gait in PAD patients is a decreased fluctuation of the vertical ground reaction force during stance phase, which has been interpreted to reflect a lower center of mass during stance [9]. The toe clearance of the swing leg has been shown to be sensitive to small angular changes in sagittal plane of the ankle, knee, and hip of the swing leg, the ankle and knee of the stance leg, as well as in the frontal plane of the stance leg at the hip joint [13]. Having a lowered center of mass is typically the result of altering one or more of these joints [14] and could lead to changes in the toe clearance profile. This in turn could cause problems with the swing leg coming in contact with the ground or another object. Changes have also been noted in the stride-to-stride differences during walking, termed gait variability, of patients with PAD. Gait variability differences found include increased standard deviations of ankle and hip ranges of motion, and increased coefficient of variation of ranges of motion at the

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ankle, knee, and hip [7]. These abnormalities are present prior to the onset of intermittent claudication pain and worsen in the presence of intermittent claudication [4]. This likely contributes to an increased risk for falls.

Another analysis associated with increased fall risk that should be investigated in patients with PAD is minimum toe clearance (MTC). MTC is the minimum vertical distance between the toe of the swing leg and the walking surface during mid-swing in the gait cycle when the foot is at its greatest velocity [13]. MTC is considered a critical gait event when assessing fall risk, because the majority of falls happen from contact between the swing leg and the ground or another object [15,16]. Based on these findings, a decreased MTC is considered to be associated with an increased risk of tripping, which can lead to falls [15]. It is therefore possible that patients with PAD have reduced toe clearance that could be leading to the increased incidence of falls. This decreased toe clearance could be present prior to the onset of claudication pain, after the onset of such pain, or possibly during both conditions. Determining the MTC during the gait cycle of patients with PAD could lead to new insights into what is causing the increased incidence of falling in this population.

When movement involves multiple repetitions of the same task differences occur between repetitions and these differences are termed variability. Variability can be quantified as the dispersion around the mean value. Standard deviation of the movement is a common way to measure the amount of variability present. When an individual is walking it only takes a single step with low toe clearance to cause a trip. If the average MTC were similar then having an increased variability in MTC would suggest that the toe is swinging closer to the ground during some steps. Thus, understanding the MTC variability associated with walking could lead to a better understanding of the mechanisms responsible for the increased incidence of falling in PAD.

There is a substantial amount of research published in the independent areas of PAD and MTC, but to date no one has investigated the possibility of reduced MTC and/or increased MTC variability present during gait with PAD despite the above mentioned gait abnormalities and increased prevalence of falls in patients with PAD. Therefore, the purpose of this study was to investigate the difference in MTC between healthy individuals and patients with PAD both in pain-free and pain conditions. The increased number of falls observed in these patients led to the following hypotheses: (1) PAD patients would exhibit a reduced MTC due to lower limb impairment, (2) PAD patients would have increased MTC variability, and (3) PAD patients would have reduced MTC means and increased MTC standard deviations following onset of symptomatic claudication pain.

Materials and methods

Participants

Eighteen PAD patients (age: mean 60.4 (SD 8.9) years; height: mean 174.7 (SD 4.7) cm; mass: mean 82.3 (SD 17.8) kg) and eighteen healthy controls (age: mean 63.8 (SD 1.7) years; height: mean 173.6 (SD 7.6) cm; mass: mean 81.5 (SD 20.6) kg) participated in this study (Table 1). The Institutional Review Boards from the respective medical centers approved all study procedures and all subjects provided informed consent prior to enrolling in the study. Patients with PAD were clinically diagnosed and recruited from the vascular surgery departments at the Omaha Veterans' Affairs Medical Center and the University of Nebraska Medical Center. Control subjects were recruited from the community and were screened to determine the absence of PAD.

Two board-certified vascular surgeons evaluated patients and controls. Patients provided a detailed history, a physical examination, and were directly observed by the vascular surgeons to ensure walking impairment was secondary to claudication pain. Exclusion criteria included those who experienced pain when walking that was not due to claudication (e.g. arthritis, low back pain, peripheral neuropathy), as well as any ambulation limiting cardiac, neuromuscular, pulmonary, or musculoskeletal disease. Controls were screened for ambulatory dysfunction and PAD. They were screened for ambulatory dysfunction in a similar manner as the patients with PAD, and were also required to have an ankle-brachial index $\geq$ 1.0.

Table 1
Demographics of PAD and control participants, values are reported as Mean (SD). ABI = Ankle Brachial Index, this is the ratio of systolic blood pressures taken in the ankle and arm, an ABI < 0.9 indicates peripheral arterial disease and was used as inclusion criteria.

	PAD patients ($n = 18$)	Controls ($n = 18$)	*P* value
Age (years)	60.4 (8.9)	64.8 (11.6)	.207
Body mass (kg)	82.3 (17.8)	80.7 (20.3)	.805
Body height (cm)	174.7 (4.7)	173.2 (7.6)	.504
ABI–L	0.71 (0.18)	> 0.90	
ABI–R	0.60 (0.22)	> 0.90	

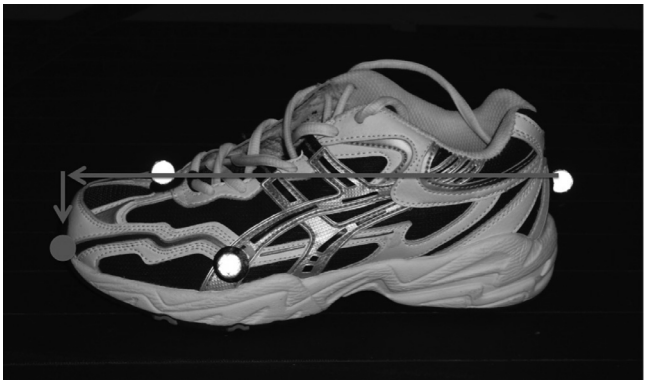

Fig. 1. Illustration of the calculation of minimum toe clearance. A virtual marker was created using Cortex (Motion Analysis Corporation, Santa Rosa, CA) software. A position was calculated by projecting a line from the heel marker through the toe marker for the length of the shoe. From this point another line was projected toward the plantar surface of the shoe the distance to the floor where the toe marker was created.

Procedures

All subjects walked on a treadmill at their self-selected pace while kinematic data was recorded (60 Hz; 12-camera Motion Analysis Corp., Santa Ana, CA) using a modified Helen Hayes marker set that has been used with the same population in previous research [5]. Patients with PAD performed one treadmill walking trial in a pain-free condition. The trial lasted until the onset of claudication pain, or for 3 mins in patients who did not reach the onset of claudication pain. After the pain-free condition was completed, subjects walked on the treadmill set at a 10% incline until the onset of moderate claudication pain, a two on the ACSM claudication pain scale [17]. The treadmill was then immediately lowered while the subject continued to walk until the pain forced them to stop, or for a maximum of 3 mins. Data for the pain condition started from the point that the treadmill was flat. Control subjects similarly walked at a self-selected pace for 3 mins while the same kinematic data was collected.

A virtual marker was created within the motion capture software (Cortex, Motion Analysis Corp., Santa Rosa, CA) using the physical markers located on the heel, fifth metatarsal and second metatarsal-phalangeal joint (Fig. 1); this prevented potential interference from a physical marker at the distal tip of the hallux. After creating the virtual toe marker, the MTC was calculated for every step using custom scripts created in Matlab (Mathworks Inc, Natick, MA). Due to