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Joint torques and powers are reduced during ambulation for both limbs in patients with unilateral claudication

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Objectives: **Symptomatic peripheral arterial disease (PAD) results in significant gait impairment. In an attempt to fully delineate and quantify these gait alterations, we analyzed joint kinematics, torques (rotational forces), and powers (rotational forces times angular velocity) in patients with PAD with unilateral claudication for both the affected and nonaffected legs.**

Methods: **Twelve patients with unilateral PAD (age, 61.69 ± 10.53 years, ankle-brachial index [ABI]: affected limb 0.59 ± 0.25; nonaffected limb 0.93 ± 0.12) and 10 healthy controls (age, 67.23 ± 12.67 years, ABI >1.0 all subjects) walked over a force platform to acquire gait kinetics, while joint kinematics were recorded simultaneously. Data were collected for the affected and nonaffected limbs during pain free (PAD-PF) and pain induced (PAD-P) trials. Kinetics and kinematics were combined to quantify torque and powers during the stance period from the hip, knee, and ankle joints.**

Results: **The affected limb demonstrated significantly ($P < .05$) reduced ankle plantar flexion torque compared to controls during late stance in both PAD-PF and PAD-P trials. There were significant reductions in ankle plantar flexion power generation during late stance for both the affected ($P < .05$) and nonaffected limbs ($P < .05$) compared to control during PAD-PF and PAD-P trials. No significant differences were noted in torque comparing the nonaffected limbs in PAD-PF and PAD-P conditions to control for knee and hip joints throughout the stance phase. Significant reductions were found in knee power absorption in early stance and knee power generation during mid stance for both limbs of the patients with PAD as compared to control ($P < .05$).**

Conclusion: **Patients with PAD with unilateral claudication demonstrate significant gait impairments in both limbs that are present even before they experience any claudication symptoms. Overall, our data demonstrate significantly reduced ankle plantar flexion torque and power during late stance with reduced knee power during early and mid stance for the affected limb. Further studies are needed to determine if these findings are dependent on the location and the severity of lower extremity ischemia and whether the changes in the nonaffected limb are the result of underlying PAD or compensatory changes from the affected limb dysfunction. (J Vasc Surg 2010;51:80-8.)**

Peripheral arterial disease (PAD) affects over 10 million people in the United States, the majority of which are elderly. Intermittent claudication is the most common presentation of PAD and consists of pain, cramping, aching, and tiredness induced by physical activity (ie, walking) and relieved with rest.[1] Intermittent claudication and its related ambulatory dysfunction are associated with poor health outcomes, physical dependence, and inactivity[2,3] severely limiting all aspects of patient functioning and quality of life.[4,5]

Currently, the ambulatory impairment produced by claudication and the degree to which it may respond to treatment are evaluated using basic time-distance tools such as gait velocity and cadence.[6] The majority of available studies indicate patients with PAD walk slower, have reduced cadence, increased stance time, shorter stride length, and a narrower step width as compared with controls.[6-9] Although these basic temporal and spatial parameters provide a description of the ambulatory dysfunction of the patient with PAD, they are unable to provide an understanding of the mechanisms responsible for this gait impairment.

A series of studies by our laboratory and others have utilized advanced biomechanical measures to identify the mechanisms underlying the gait impairment of patients with PAD. Scott-Pandorf et al[26] demonstrated several mechanisms leading to PAD gait dysfunction. Patients with PAD walk with decreased fluctuations of center of gravity, have significantly decreased peak propulsion force, and exhibit a reduced ability to swing their legs forward. Crowther et al[7] observed abnormal ankle plantar flexion in early stance, knee range of motion in stance phase, and hip extension in late stance[10] while Chen et al[20] demonstrated significant torque alterations at the ankle and hip.

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To more clearly delineate the joint muscular responses and their contributions in patients with claudication, we have employed advanced biomechanical analysis in the form of joint torques and powers. The joint torque is the net result of all forces acting around a joint. Positive torque values represent an extensor response, while negative values indicate a flexor response. Joint powers are the product of net torque across a joint and the angular velocity of the joint. Positive joint power indicates that energy is being generated and is associated with concentric muscular contraction, while negative power indicates that energy is being absorbed and is associated with eccentric muscular contraction. The utility of joint powers is their unique ability to point to specific neuromuscular deficits in pathologic gait and guide subsequent treatment. Joint powers have identified the alterations in knee osteoarthritis, anterior cruciate ligament reconstruction,[11,12] below-knee amputees,[13] and patients with hip arthroplasty,[14] while providing unique rehabilitation protocols in patients undergoing anterior cruciate ligament reconstruction.[15] In addition, joint powers have characterized the gait mechanics of the elderly[16-19] and identified the risk for falls in healthy elderly populations. Similar insights can be gained from advanced biomechanical analysis of patients with PAD.

Using this approach in our previous work, we have identified weakness in the posterior compartment muscles of the calf as a consistent and key factor underlying the PAD gait adaptations.[20] Our previous studies investigated patients with bilateral claudication. Clinically, however, many patients present with unilateral symptoms having both an affected limb (AL) and a nonaffected limb (NAL). Therefore, the purpose of our study was to utilize advanced biomechanical analysis to determine the gait impairment of the individual limbs of unilateral patients with PAD. Based on our previous work, we hypothesized that the AL of patients with PAD would demonstrate significant differences compared to the nonaffected and the control (CON) limbs while the patients walked before the onset of claudication, these differences would variably worsen after the onset of claudication symptoms. We also hypothesized that the NALs would demonstrate no differences as compared to CON.

METHODS

Subject inclusion and exclusion criteria. Twelve male patients (age, 61.69 ± 10.53 years, ankle brachial index [ABI]: AL 0.59 ± 0.25; NAL 0.93 ± 0.12) diagnosed with moderate arterial occlusive disease and unilateral claudication were recruited from the vascular surgery clinics of the VA Nebraska and Western Iowa and University of Nebraska Medical Centers. In addition, 10 age-, gender-, body mass-, and height-matched healthy CONs (age, 66.27 ± 9.22 years; ABI, 1.1 ± 0.11) were recruited from the community and volunteered to participate. Patients and CONs were screened and evaluated by two board-certified vascular surgeons. PAD and CON patients with ambulation-limiting cardiac, pulmonary, neuromuscular, musculoskeletal disease, or those who experienced pain or discomfort during walking for any reason other than claudication were excluded. Patient evaluation included resting ABI (a measurement below 0.9 was present in the AL of all subjects with unilateral claudication that was measured in our VA and University of Nebraska Medical Center Vascular Laboratories), a detailed history, physical examination, and a direct assessment/observation of the patient's walking impairment. All PAD subjects recruited had no previous attempts at revascularization.

CON subjects had an ABI greater than 1.0 and no subjective or objective ambulatory dysfunction. CONs were screened in a similar fashion as patients with PAD and were excluded for the same ambulation-limiting comorbidities. Informed consent was obtained from all subjects prior to data collection according to the guidelines of the Institutional Review Boards of the medical centers. The gait of all recruited participants was tested in our Biomechanics Laboratory.

Experimental procedure and data collection. Kinematic and kinetic parameters from the ankle, knee, and hip joints were evaluated in patients with PAD from both the ALs and NALs before (pain free [PAD-PF]) and after onset of claudication symptoms (pain [PAD-P]). The limbs were evaluated during early stance (weight acceptance phase), mid stance (weight transfer phase), and late stance (weight propulsion phase). To assess the ambulatory deficits of the ALs and NALs, patients with PAD were compared to height-, gender-, mass-, and age-matched healthy CONs. Prior to data collection, reflective markers were placed at specific anatomic locations of each subject's lower limb utilizing the modified Helen Hayes marker set.[21,22] Each subject walked with his or her self-selected pace on a 10-m pathway while the three-dimensional marker trajectories and ground reaction force data were collected simultaneously. The three-dimensional marker trajectories were collected with an eight high-speed real-time camera system (EvaRT 5.0, Motion Analysis Corp, Santa Rosa, Calif) surrounding the walkway sampling at 60 Hz. The ground reaction force data were acquired with a Kistler force platform (Kistler Instrument, Winterthur, Switzerland) located in the middle of the walkway sampling at 600 Hz.

Each patient with PAD was tested first in the PAD-PF condition (before the onset of claudication symptoms), followed by the PAD-P (after the onset of claudication symptoms). For the PAD-PF condition, a mandatory rest period of at least 1 minute occurred between walking trials to ensure that any pain symptoms had subsided. Once patients completed all PAD-PF trials, claudication was induced. To accomplish this, a clinical protocol was used that consisted of walking on a treadmill set at 10% grade and at a speed of 0.67 m/second[23,24] until the onset of pain. At this time, patients were immediately removed from the treadmill and returned to the collection walkway to acquire the data for the pain condition without the mandatory resting periods between trials. The CON subjects completed five walking trials with mandatory rest of 1 minute between the trials. A total of five successful trials were collected from each limb of the subjects for each condition.

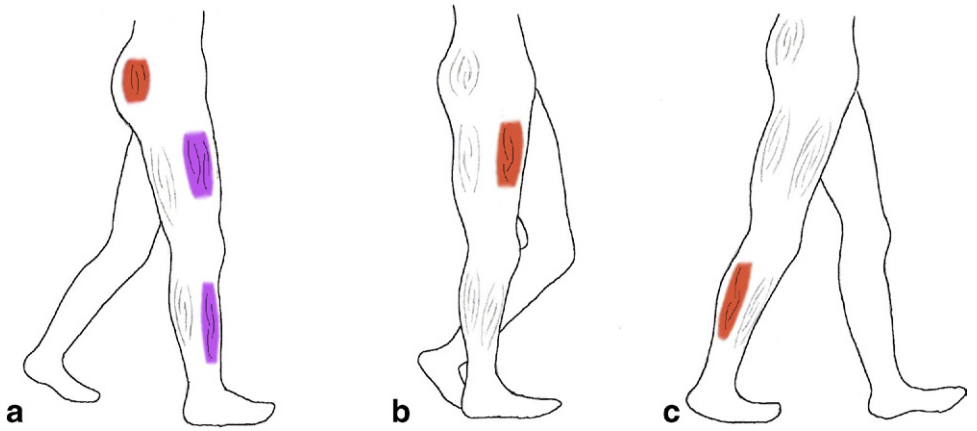

Fig 1. An illustration of the stance phase of walking with the dominant flexor and extensor muscle groups that are involved in the three phases is produced. The dominant muscle groups are identified in red if they contract concentrically and in purple if they contract eccentrically. a, Early stance phase lasts from ipsilateral heel strike to contralateral toe off thus covering the first double support phase (initial 20% of stance). The right leg is accepting the majority of body weight as it descends from previously being in single support on the left leg. In this phase, the right hip extensors concentrically contract to extend the hip, the knee extensors eccentrically contract to allow the knee to bend, and the ankle dorsiflexors eccentrically contract to maintain ankle dorsiflexion. b, Mid stance phase lasts from contralateral (here left) toe off until contralateral heel strike. During single support, the body is at its highest point over the extended ipsilateral leg. The body has maximum potential energy preparing to fall forward for the next double support. Limited muscular contractions are needed during this phase except when the knee extensors contract concentrically to extend the knee and straighten the leg. c, Late stance lasts from contralateral heel strike to ipsilateral toe off. It is the final 20% of stance and is the second double support phase. In this phase, the body is propelled forward onto the extended left leg mainly by the action of the ankle plantar flexors. Functionally, these muscles contract concentrically and accelerate the leg and the trunk forward and upward over the left leg thus providing forward progression and weight support.

A successful walking trial was determined by the subject's foot being completely within the force platform.

Data analysis. Data from the three-dimensional marker trajectories and ground reaction forces were combined to calculate the joint torques and powers for the sagittal plane during the stance phase of walking (from heel touchdown to toe off). The limbs were evaluated during early stance (weight acceptance phase), mid stance (weight transfer phase), and late stance (weight propulsion phase) (Fig 1). A low-pass fourth-order Butterworth filter with a 7 Hz cutoff frequency was used to smooth the marker trajectories during postdata processing. An inverse dynamic technique was performed to calculate joint torques and joint muscle powers from the kinematic (displacement velocities and accelerations derived from the three-dimensional marker trajectories) and the kinetic (derived from the ground reaction forces) data.[25] Joint torque was calculated as the summation of all torques acting around a specific joint. These torques are the product of all muscular, ligament, frictional, gravitational, inertial, and ground reaction forces acting on the joint. Positive torque values represent extensor torques while negative values indicate flexor torques. Joint muscle power was calculated as the product of the net torque at a joint (T_j) and joint angular velocity (ω_j) or $P_j = T_j x\, \omega_j$. Power measurements can be expressed positively or negatively. Positive power indicates energy is being generated (concentric muscular contractions) and negative power indicates energy is being absorbed (eccentric muscular contractions) by the joint muscle group under study. Joint torques and joint muscle powers were normalized by body weight and expressed as a percentage (100%) during stance phase from heel strike (0% stance) to toe-off (100% stance). Peak torques were measured for the following muscle groups: ankle dorsiflexors, ankle plantar flexors, knee extensors, knee flexors, hip extensors, and hip flexors. The peak variables indentified for joint powers were: ankle power absorption in mid stance (A1), ankle power generation in late stance (A2), knee power absorption in early stance (K1), knee power generation in early stance (K2), knee power absorption in late stance (K3), hip power generation in early stance (H1), hip power absorption in mid stance (H2), and hip power generation in late stance (H3). All normalization occurred after the peak points were determined to ensure that the normalization did not distort these values. Joint torques and joint powers were calculated and normalized using custom software in Matlab (Matlab 2007, Mathworks Inc, Concord, Mass).

Statistical analysis. Group means for all dependent variables were calculated for each testing condition (PAD-PF and PAD-P) for all limbs. Thus, 12 ALs and 12 NALs were evaluated for the patients with PAD in each condition compared to 20 limbs for the CON group. A two-by-two fully repeated measures analysis of variance was used to compare the two limbs for both PAD-PF and

Table I. Baseline characteristics of patients with peripheral arterial disease (PAD) and healthy controls

Clinical characteristics	*Control (n = 20 limbs)*	*PAD (n = 24 limbs)*	P *value*
Age (years)	66.27 ± 9.22	61.69 ± 10.53	ns
Body mass (kg)	77.89 ± 10.65	84.65 ± 20.24	ns
Body height (m)	1.74 ± 0.08	1.72 ± 0.08	ns
Disease duration (years)	0	6.25 ± 3.84	N/A
ABI			
Nonaffected limb		.93 ± .12	ns
Affected limb		.59 ± .25	
Right for control	1.1 ± .12		
Left for control	1.1 ± .08		<.05
Smokers, n (%)	8 (80)	7 (58.3)	ns
Hypertension, n (%)	0 (0)	5 (41.7)	<.05
Diabetes mellitus, n (%)	0 (0)	1 (8.3)	ns
Dyslipidemia, n (%)	0 (0)	9 (75)	<.05
BMI	25.60 ± 2.94	27.42 ± 4.44	ns

ABI, Ankle brachial index; *BMI,* body mass index; *ns,* statistically nonsignificant; *N/A,* not applicable.
Values are presented as means ± standard deviations.

PAD-P conditions. Independent *t* tests were used to compare both conditions and both limbs of the PAD group with the CON group. Independent *t* tests were also used to compare the differences between PAD and CON group demographics. The level of significance was set to 0.05. Values are presented in the tables and figures as means ± standard deviations. The SPSS Base 12.0 statistical software (SPSS Inc, Chicago, Ill) was used to perform the statistical analysis.

RESULTS

Subjects. Twelve patients with PAD with clinically diagnosed aortoiliac (n = 4), femoropopliteal (n = 4), and multilevel (n = 4) occlusive disease and calf claudication were evaluated. All patients had Rutherford category 2 moderate claudication symptoms. Ten CON subjects with absence of claudication were also included (Table I).

Joint torques and powers

Early stance. Significant reduction in ankle dorsiflexion torque was noted for the AL during early stance in the PAD-P condition as compared to CONs. The knee extensor torque was reduced during early stance for the AL in both PAD-PF and PAD-P conditions as compared to CONs (Table II; Fig 2). Knee power absorption during early stance was significantly reduced for the AL in both PAD-PF and PAD-P conditions as compared to CONs (Table III; Fig 3) whereas reduction for the NAL was noted in the PAD-PF condition (Table III; Fig 4). The knee power generation during early stance was significantly reduced for both limbs in the PAD-PF and PAD-P conditions as compared to CONs. In addition, the knee power generation during early stance was significantly reduced in the PAD-PF condition as compared to PAD-P primarily in the NAL (Table III).

Midstance. Hip power absorption in mid stance was significantly reduced in the NAL in both PAD-PF and PAD-P conditions as compared to CONs (Table III).

Late stance. Significant reduction in ankle plantar flexion torque was noted for the AL in both PAD-PF and PAD-P conditions during late stance as compared to CONs (Table III; Fig 2). Ankle power generation during late stance was significantly reduced for the limbs as compared to CONs for both the PAD-PF and PAD-P conditions (Table III; Figs 3 and 4). In addition, significant reductions in ankle power generation were noted during the PAD-P condition compared to the PAD-PF condition for both limbs of the patients with PAD (Table III).

DISCUSSION

The present study is the first to provide detailed quantitative analysis of the joint torque and joint power changes in patients with PAD with unilateral intermittent claudication. While prior works have examined the biomechanics of symptomatic PAD limbs,[7,26] the current study is unique in simultaneously evaluating symptomatic and asymptomatic limbs of patients with PAD with classic symptom unilateral claudication. Joint torques and joint powers were evaluated while patients with PAD walked both before and after the onset of claudication (PAD-PF and PAD-P conditions, respectively) and were compared to those of gender-, height-, mass-, and age-matched healthy CONs. Our data demonstrate that the gait of claudicating patients is significantly altered for both limbs in both the PAD-PF and PAD-P conditions.

Our results continue to identify a weakness in the posterior compartment muscles of the calf as the primary dysfunction operating in the patient with PAD producing significantly altered ankle propulsion during late stance.[20] Compared to CONs, patients with PAD have decreased power generation in both their limbs as they try to propel toward swing in late stance in both PAD-PF and PAD-P conditions (Table III; Figs 2 and 3). The decreased power generation during plantar flexion points to a significant weakness of the posterior calf muscles (primarily the gastrocnemius and soleus), which constitutes the dominant muscle group responsible for ankle plantar flexion (push-off initiating the swing phase). Weakness of the posterior calf muscles is consistent with this muscle group being the "functional end organ" in lower extremity ischemia. This hypothesis is further supported by findings demonstrating that patients with PAD have significantly decreased ankle plantar flexor strength[3,27-29] and decreased ankle plantar flexor torque. Importantly, advanced biomechanical analysis demonstrated the specific dysfunction with a limited number of patients (n = 22) compared to other methodologies (n = 500-1500). Functionally, in late stance the gastrocnemius and the soleus both concentrically contract to propel the body forward and initiate leg swing while decelerating the downward motion of the trunk (ie, providing forward progression and support).[30] Our advanced biomechanical analyses clearly identifies the most definable and obvious deficit in patients with PAD, regardless of the

Table II. Group means and standard deviations for joint torques of the ankle, knee, and hip joint for peripheral arterial disease (PAD) and control groups[a,c]

		PAD (n = 24 limbs)			
		Pain Free (PAD-PF)		*Pain (PAD-P)*	
	Control (n = 20 limbs)	*Nonaffected limb*	*Affected limb*	*Nonaffected limb*	*Affected limb*
ADT	−0.36 ± 0.09	−0.38 ± 0.20	−0.29 ± 0.13	−0.42 ± 0.30	−0.23 ± 0.15[b]
APT	1.31 ± 0.28	1.32 ± 0.16	1.18 ± 0.25[a,c]	1.27 ± 0.18	1.11 ± 0.27[b]
KET	0.82 ± 0.18	0.61 ± 0.30	0.58 ± 0.27[a]	0.69 ± 0.41	0.59 ± 0.37[b]
KFT	−0.14 ± 0.12	−0.23 ± 0.21	−0.14 ± 0.22	−0.20 ± 0.28	−0.13 ± 0.26
HET	0.98 ± 0.49	0.83 ± 0.33	0.72 ± 0.15	0.80 ± 0.23	0.78 ± 0.24
HFT	−0.95 ± 0.21	−0.72 ± 0.39	−0.96 ± 0.51	−0.76 ± 0.43	−0.90 ± 0.65

ADT, Ankle dorsiflexion torque; *APT,* ankle plantar flexion torque; *KET,* extensor torque; *KFT,* flexor torque; *HET,* hip extensor torque; *HFT,* hip flexor torque.
The units for all values are N*m/kg.
[a] $P < .05$, Significant differences between groups (PAD-PF, affected limb vs control).
[b] $P < .05$, Significant differences between groups (PAD-P, affected limb vs control).
[c] $P < .05$, Significant differences between testing conditions (PAD-PF vs PAD-P).

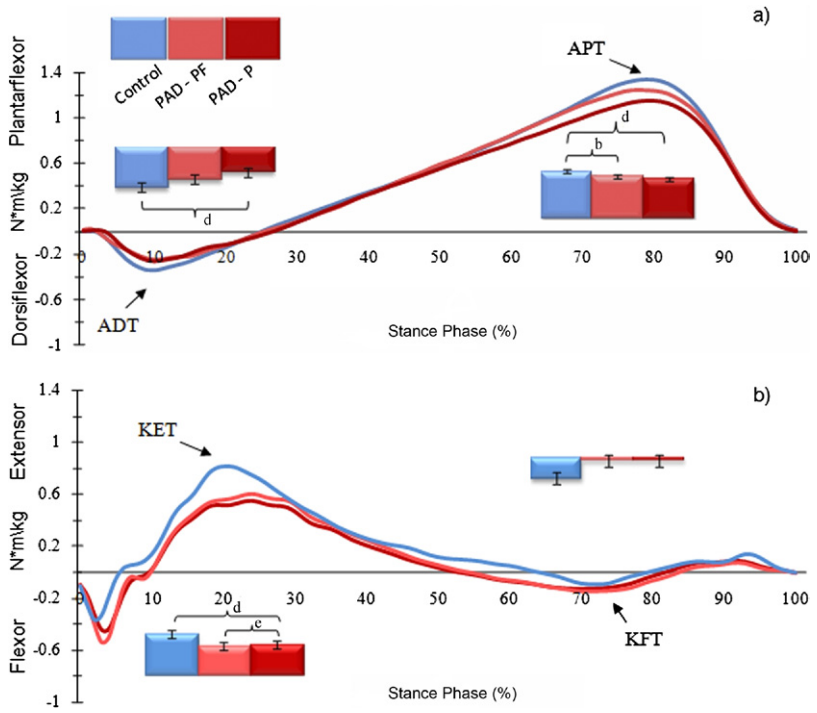

Fig 2. The ensemble-average joint torque curves of the affected limb for the patients with peripheral arterial disease-pain free (PAD-PF) and peripheral arterial disease-with pain (PAD-P; n = 24 limbs) and the healthy controls (control, n = 20 limbs) during the stance phase for the **(a)** ankle and **(b)** knee joints. Torques are normalized to body mass in kg. Error bars represent the standard deviation of the mean values. *ADT,* Ankle dorsiflexion torque; *APT,* ankle plantar flexion torque; *KET,* extensor torque; *KFT,* flexor torque.
[b] $P < .05$, Significant differences between groups (PAD-PF affected limb vs control).
[d] $P < .05$, Significant differences between groups (PAD-P affected limb vs control).
[c] $P < .05$, Significant differences between testing conditions (PAD-PF vs PAD-P).

degree of limb ischemia, as a failure of the ankle plantar flexors to optimally contract producing decreased power output in late stance.

There were notable findings at the knee and hip for the current study when examining torque and power data. Knee extensor torque (Fig 2) in early stance was decreased in both PAD-PF and PAD-P conditions for the AL as compared to CONs. The knee power absorption in early stance and knee power generation in mid stance (both serving to decelerate trunk descent on the supporting limb)

Table III. Group means and standard deviations for joint powers of the ankle, knee, and hip joint for peripheral arterial disease (PAD) and control groups

		PAD (n = 24 limbs)			
		Pain free (PAD-PF)		*Pain (PAD-P)*	
	Control (n = 20 limbs)	*Nonaffected limb*	*Affected limb*	*Nonaffected limb*	*Affected limb*
A1	−0.52 ± 0.21	−0.37 ± 0.35	−0.43 ± 0.18	−0.53 ± 0.16	−0.43 ± 0.15
A2	4.00 ± 0.88	2.65 ± 0.92[a,e]	2.49 ± 0.46[b,e]	2.39 ± 0.67[c]	2.05 ± 0.59[d]
K1	−0.73 ± 0.22	−0.52 ± 0.40[a]	−0.36 ± 0.21[b]	−0.75 ± 0.74	−0.36 ± 0.32[d]
K2	0.62 ± 0.25	0.31 ± 0.23[a,e]	0.25 ± 0.25[b,e]	0.41 ± 0.28[c]	0.26 ± 0.31[d]
K3	−0.73 ± 0.23	−0.67 ± 0.57	−1.09 ± 1.05	−0.66 ± 0.53	−1.00 ± 1.20
H1	0.42 ± 0.20	0.39 ± 0.21	0.38 ± 0.20	0.41 ± 0.20	0.31 ± 0.29
H2	−0.78 ± 0.23	−0.65 ± 0.36[a]	−0.68 ± 0.35	−0.58 ± 0.54[c]	−0.68 ± 0.45
H3	0.76 ± 0.29	0.77 ± 0.37	0.78 ± 0.51	0.57 ± 0.42	0.62 ± 0.55

A1, Ankle power absorption in late mid stance; *A2,* ankle power generation in late stance; *K1,* knee power absorption in early stance; *K2,* knee power generation in early mid stance; *K3,* knee power absorption in late stance; *H1,* hip power generation in early stance; *H2,* hip power absorption in mid stance; *H3,* hip power generation in late stance.
The units for all values are watts/kg.
[a] $P < .05$, Significant differences between groups (PAD-PF, nonaffected limb vs control).
[b] $P < .05$, Significant differences between groups (PAD-PF, affected limb vs control).
[c] $P < .05$, Significant differences between groups (PAD-P, nonaffected limb vs control).
[d] $P < .05$, Significant differences between groups (PAD-P, affected limb vs control).
[e] $P < .05$, Significant differences between testing conditions (PAD-PF vs PAD-P).

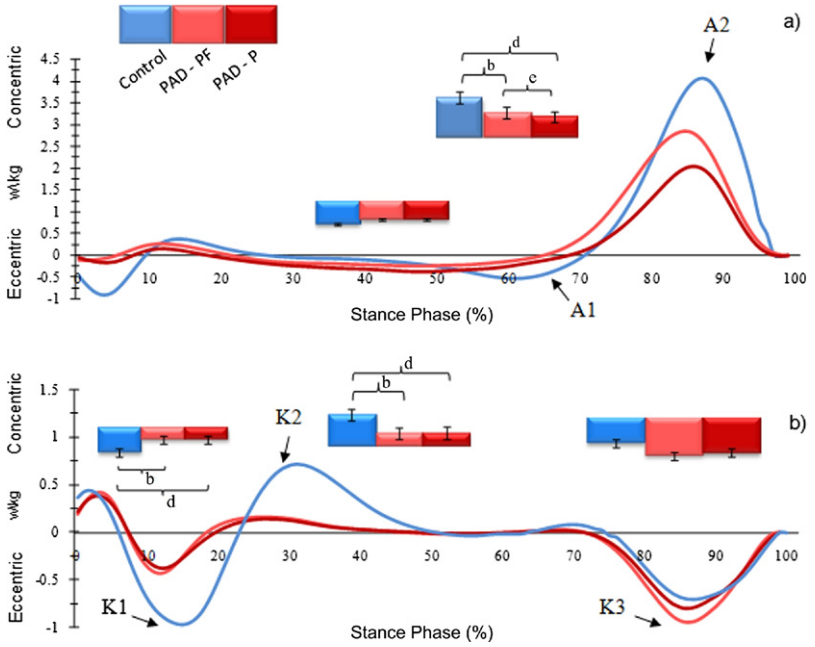

Fig 3. The ensemble-average joint power curves of the affected limb for the patients with peripheral arterial disease-pain free (PAD-PF) and peripheral arterial disease-with pain (PAD-P; n = 24 limbs) and the healthy controls (control, n = 20 limbs) during the stance phase for the **(a)** ankle and **(b)** knee joints. *Note:* A1 ankle power absorption in late mid stance, A2 ankle power generation in late stance, K1 knee power absorption in early stance, K2 knee power generation in early stance, K3 knee power absorption in late stance. Error bars represent the standard deviation of the mean values.
[b] $P < .05$, Significant differences between groups (PAD-PF affected limb vs control).
[d] $P < .05$, Significant differences between groups (PAD-P affected limb vs control).
[e] $P < .05$, Significant differences between testing conditions (PAD-PF vs PAD-P).

for both limbs of the patients with PAD were significantly reduced as compared to CONs. In addition, hip power absorption (stabilizing the trunk on the moving lower limb in preparation for push-off) was significantly reduced during mid stance for the NAL during PAD-PF and PAD-P trials as compared to CONs. Our current data in patients with unilateral claudication along with our recently published work in patients with bilateral claudication,[20,31] sug-

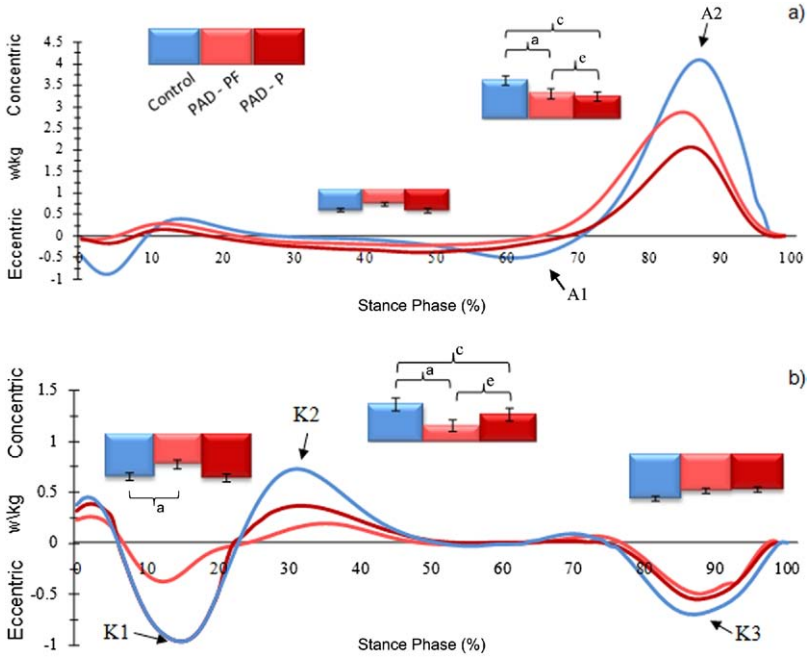

Fig 4. The ensemble-average joint power curves of the non-affected limb for the patients with peripheral arterial disease-pain free (PAD-PF) and peripheral arterial disease-with pain (PAD-P; n = 24 limbs) and the healthy controls (control, n = 20 limbs) during the stance phase for the **(a)** ankle and **(b)** knee, joints. *A1,* Ankle power absorption in late mid stance; *A2,* ankle power generation in late stance; *K1,* knee power absorption in early stance; *K2,* knee power generation in early mid stance; *K3,* knee power absorption in late stance. Error bars represent the standard deviation of the mean values.

[a] $P < .05$, Significant differences between groups (PAD-PF, nonaffected limb vs control).

[c] $P < .05$, Significant differences between groups (PAD-P, nonaffected limb vs control).

[e] $P < .05$, Significant differences between testing conditions (PAD-PF vs PAD-P).

gest that alterations at the knee and hip result in abnormal trunk support during walking in patients with PAD. Combined with the abnormal power generation at the ankle level in late stance, the claudicating patient may be unable to accept and support the weight of the trunk, especially after the onset of claudication pain. Future studies will need to explore the gait handicap of patients with PAD with aortoiliac occlusive disease (ie, buttock and thigh claudication) compared to patients with femoral-popliteal occlusive disease (ie, calf claudication) to determine if these patterns persist.

The current study examines unilateral claudication patients with a clear focus on the "asymptomatic" limb. Most vascular specialists in a clinical setting would focus solely on the symptomatic limb, especially with an asymptomatic contralateral limb and normal ABI. Additionally, most clinicians would assume the normal limb would compensate for the dysfunction of the AL. Several important findings should be noted for this asymptomatic limb. First, despite absence of symptoms, the NAL demonstrates significant reductions in joint powers when compared to the CON limbs. These differences are demonstrated clearly for the ankle power generation at late stance, knee power absorption and generation in early stance, and hip power absorption at mid stance. Secondly, when comparing the NAL to the AL directly, no statistically significant differences were found indicating similar joint muscular responses in both legs. Therefore, our data demonstrate abnormal gait biomechanics for the NAL in the unilateral claudicant.

The main pathophysiologic mechanism operating in claudication is exercise-induced ischemia of the muscles in the symptomatic limbs, which is followed by reperfusion at rest.[32-37] These repeated cycles of ischemia/reperfusion have been shown to be responsible for the myopathy of claudicating muscles, which is principally characterized by mitochondrial dysfunction and oxidative damage. Interestingly, in two studies[38,39] evaluating levels of mitochondrial DNA damage in muscles from ALs and NALs of patients with unilateral PAD, Bhat et al[38] demonstrated that mitochondrial damage was present in both limbs despite a normal ABI and absence of symptoms in the NAL. Our findings, coupled with those of Bhat et al,[38] suggest that ischemia/reperfusion of the AL may have an effect (possibly by systemic oxidative stress or another neuro/humoral pathway) on the NAL. An alternative explanation for our findings is subclinical occlusive disease in the nonaffected and asymptomatic limbs not detected at rest but present

with exertion. Although our patients had normal resting ABIs and no symptoms in their NAL, we did not evaluate them using exercise treadmill testing, which could have revealed occlusive disease in the NAL that is not discernible by ABI measurements at rest. Finally, it is possible that the NAL may be suffering overuse injury because of an attempt by the patient with PAD to protect the symptomatic limb, or in contrast the NAL may be deconditioned because of the limitations to ambulation posed by the AL. Regardless of the mechanism, it is clear that the NAL in unilateral PAD is not simply an innocent bystander.

In summary, biomechanical analysis using joint torques and powers indicates significant abnormalities in the gait of NALs and ALs in both PAD-PF and PAD-P conditions for patients with unilateral claudication. Our research work points to significant calf muscle dysfunction leading to an inability to propel the body as the primary gait deficit in patients with PAD. Additional impairments at the knee and hip affecting weight transfer are also present. These findings demonstrate that advanced biomechanical analysis correlates with basic laboratory data and can be used to fully define the underlying gait handicap of patients with PAD. Advanced biomechanical gait analysis, therefore, holds the potential to assess, in a limited number of patients, the effect of exercise walking programs, medication regimens, and revascularization to determine the degree to which the gait dysfunction of claudicating patients is ultimately recoverable.

AUTHOR CONTRIBUTIONS

Conception and design: PK, IP, NS, JJ
Analysis and interpretation: PK, IP, SM, TL, NS, JJ
Data collection: PK, SM, JJ
Writing the article: PK, IP, NS, JJ
Critical revision of the article: IP, NG, TL, JJ
Final approval of the article: PK, IP, SM, TL, NS, JJ
Statistical analysis: PK, SM, JJ
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REFERENCES

1. Hooi JD, Kester AD, Stoffers HE, Overdijk MM, van Ree JW, Knottnerus JA. Incidence of and risk factors for asymptomatic peripheral arterial occlusive disease: a longitudinal study. Am J Epidemiol 2001; 153:666-72.
2. Atkins LM, Gardner AW. The relationship between lower extremity functional strength and severity of peripheral arterial disease. Angiology 2004;55:347-55.
3. Gardner AW, Clancy RJ. The relationship between ankle-brachial index and leisure-time physical activity in patients with intermittent claudication. Angiology 2006;57:539-45.
4. Liles DR, Kallen MA, Petersen LA, Bush RL. Quality of life and peripheral arterial disease. J Surg Res 2006;136:294-301.
5. Regensteiner JG, Stewart KJ. Established and evolving medical therapies for claudication in patients with peripheral arterial disease. Nat Clin Pract Cardiovasc Med 2006;3:604-10.
6. McDermott MM, Ohlmiller SM, Liu K, Guralnik JM, Martin GJ, Pearce WH, Greenland P. Gait alterations associated with walking impairment in people with peripheral arterial disease with and without intermittent claudication. J Am Geriatr Soc 2001;49:747-54.
7. Crowther RG, Spinks WL, Leicht AS, Quigley F, Golledge J. Relationship between temporal-spatial gait parameters, gait kinematics, walking performance, exercise capacity, and physical activity level in peripheral arterial disease. J Vasc Surg 2007;45:1172-8.
8. McDermott MM, Mehta S, Liu K, Guralnik JM, Martin GJ, Criqui MH, Greenland P. Leg symptoms, the ankle-brachial index, and walking ability in patients with peripheral arterial disease. J Gen Intern Med 1999;14:173-81.
9. Scherer SA, Bainbridge JS, Hiatt WR, Regensteiner JG. Gait characteristics of patients with claudication. Arch Phys Med Rehabil 1998;79: 529-31.
10. Crowther RG, Spinks WL, Leicht AS, Quigley F, Golledge J. Lower limb movement variability in patients with peripheral arterial disease. Clin Biomech (Bristol, Avon) 2008;23:1080-5.
11. Kaufman KR, Hughes C, Morrey BF, Morrey M, An KN. Gait characteristics of patients with knee osteoarthritis. J Biomech 2001;34: 907-15.
12. McGibbon CA, Krebs DE. Compensatory gait mechanics in patients with unilateral knee arthritis. J Rheumatol 2002;29:2410-9.
13. Centomo H, Amarantini D, Martin L, Prince F. Kinematic and kinetic analysis of a stepping-in-place task in below-knee amputee children compared to able-bodied children. IEEE Trans Neural Syst Rehabil Eng 2007;15:258-65.
14. Loizeau J, Allard P, Duhaime M, Landjerit B. Bilateral gait patterns in subjects fitted with a total hip prosthesis. Arch Phys Med Rehabil 1995;76:552-7.
15. DeVita P, Hortobagyi T, Barrier J. Gait biomechanics are not normal after anterior cruciate ligament reconstruction and accelerated rehabilitation. Med Sci Sports Exerc 1998;30:1481-8.
16. DeVita P, Hortobagyi T. Age causes a redistribution of joint torques and powers during gait. J Appl Physiol 2000;88:1804-11.
17. Kerrigan DC, Todd MK, Della Croce U, Lipsitz LA, Collins JJ. Biomechanical gait alterations independent of speed in the healthy elderly: evidence for specific limiting impairments. Arch Phys Med Rehabil 1998;79:317-22.
18. McGibbon CA, Krebs DE. Age-related changes in lower trunk coordination and energy transfer during gait. J Neurophysiol 2001;85: 1923-31.
19. Riley PO, DellaCroce U, Kerrigan DC. Effect of age on lower extremity joint moment contributions to gait speed. Gait Posture 2001;14: 264-70.
20. Chen SJ, Pipinos I, Johanning J, Radovic M, Huisinga JM, Myers SA, Stergiou N. Bilateral claudication results in alterations in the gait biomechanics at the hip and ankle joints. J Biomech 2008;41:2506-14.
21. Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. J Orthop Res 1990;8: 383-92.
22. Houck J, Yack HJ, Cuddeford T. Validity and comparisons of tibiofemoral orientations and displacement using a femoral tracking device during early to mid stance of walking. Gait Posture 2004;19:76-84.
23. Kirby RL, Marlow RW. Reliability of walking endurance with an incremental treadmill test. Angiology 1987;38:524-9.
24. DiBianco R, Morganroth J, Freitag JA, Ronan JA Jr, Lindgren KM, Donohue DJ, et al. Effects of nadolol on the spontaneous and exercise-provoked heart rate of patients with chronic atrial fibrillation receiving stable dosages of digoxin. Am Heart J 1984;108(4 Pt 2):1121-7.
25. Winter DA, Patla AE, Frank JS, Walt SE. Biomechanical walking pattern changes in the fit and healthy elderly. Phys Ther 1990;70:340-7.
26. Scott-Pandorf MM, Stergiou N, Johanning JM, Robinson L, Lynch TG, Pipinos II. Peripheral arterial disease affects ground reaction forces during walking. J Vasc Surg 2007;46:491-9.
27. Kuo HK, Yu YH. The relation of peripheral arterial disease to leg force, gait speed, and functional dependence among older adults. J Gerontol A Biol Sci Med Sci 2008;63:384-90.
28. McDermott MM, Tian L, Ferrucci L, Liu K, Guralnik JM, Liao Y, et al. Associations between lower extremity ischemia, upper and lower extremity strength, and functional impairment with peripheral arterial disease. J Am Geriatr Soc 2008;56:724-9.

29. Scott-Okafor HR, Silver KK, Parker J, Almy-Albert T, Gardner AW. Lower extremity strength deficits in peripheral arterial occlusive disease patients with intermittent claudication. Angiology 2001;52:7-14.
30. Neptune RR, Kautz SA, Zajac FE. Contributions of the individual ankle plantar flexors to support, forward progression and swing initiation during walking. J Biomech 2001;34:1387-98.
31. Celis R, Pipinos II, Scott-Pandorf MM, Myers SA, Stergiou N, Johanning JM. Peripheral arterial disease affects kinematics during walking. J Vasc Surg 2009;49:127-32.
32. Pipinos II, Judge AR, Selsby JT, Zhu Z, Swanson SA, Nella AA, Dodd SL. The myopathy of peripheral arterial occlusive disease: part 1. Functional and histomorphological changes and evidence for mitochondrial dysfunction. Vasc Endovascular Surg 2007;41:481-9.
33. Pipinos II, Judge AR, Selsby JT, Zhu Z, Swanson SA, Nella AA, Dodd SL. The myopathy of peripheral arterial occlusive disease: Part 2. Oxidative stress, neuropathy, and shift in muscle fiber type. Vasc Endovascular Surg 2008;42:101-12.
34. Pipinos II, Judge AR, Zhu Z, Selsby JT, Swanson SA, Johanning JM, et al. Mitochondrial defects and oxidative damage in patients with peripheral arterial disease. Free Radic Biol Med 2006;41:262-9.
35. Pipinos II, Sharov VG, Shepard AD, Anagnostopoulos PV, Katsamouris A, Todor A, et al. Abnormal mitochondrial respiration in skeletal muscle in patients with peripheral arterial disease. J Vasc Surg 2003;38: 827-32.
36. Pipinos II, Shepard AD, Anagnostopoulos PV, Katsamouris A, Boska MD. Phosphorus 31 nuclear magnetic resonance spectroscopy suggests a mitochondrial defect in claudicating skeletal muscle. J Vasc Surg 2000;31:944-52.
37. Weber F, Ziegler A. Axonal neuropathy in chronic peripheral arterial occlusive disease. Muscle Nerve 2002;26:471-6.
38. Bhat HK, Hiatt WR, Hoppel CL, Brass EP. Skeletal muscle mitochondrial DNA injury in patients with unilateral peripheral arterial disease. Circulation 1999;99:807-12.
39. Brass EP, Wang H, Hiatt WR. Multiple skeletal muscle mitochondrial DNA deletions in patients with unilateral peripheral arterial disease. Vasc Med 2000;5:225-30.

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