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Supervised walking exercise therapy improves gait biomechanics in patients with peripheral artery disease

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ABSTRACT

Objective: In patients with peripheral artery disease (PAD), supervised exercise therapy is a first line of treatment because it increases maximum walking distances comparable with surgical revascularization therapy. Little is known regarding gait biomechanics after supervised exercise therapy. This study characterized the effects of supervised exercise therapy on gait biomechanics and walking distances in claudicating patients with PAD.

Methods: Forty-seven claudicating patients with PAD underwent gait analysis before and immediately after 6 months of supervised exercise therapy. Exercise sessions consisted of a 5-minute warmup of mild walking and stretching of upper and lower leg muscles, 50 minutes of intermittent treadmill walking, and 5 minutes of cooldown (similar to warmup) three times per week. Measurements included self-perceived ambulatory limitations measured by questionnaire, the ankle-brachial index (ABI), walking distance measures, maximal plantar flexor strength measured by isometric dynamometry, and overground gait biomechanics trials performed before and after the onset of claudication pain. Paired *t*-tests were used to test for differences in quality of life, walking distances, ABI, and maximal strength. A two-factor repeated measures analysis of variance determined differences for intervention and condition for gait biomechanics dependent variables.

Results: After supervised exercise therapy, quality of life, walking distances, and maximal plantar flexor strength improved, although the ABI did not significantly change. Several gait biomechanics parameters improved after the intervention, including torque and power generation at the ankle and hip. Similar to previous studies, the onset of claudication pain led to a worsening gait or a gait that was less like healthy individuals with a pain-free gait.

Conclusions: Six months of supervised exercise therapy produced increases in walking distances and quality of life that are consistent with concurrent improvements in muscle strength and gait biomechanics. These improvements occurred even though the ABI did not improve. Future work should examine the benefits of supervised exercise therapy used in combination with other available treatments for PAD. (J Vasc Surg 2020;71:575-83.)

Keywords:
Claudication; Walking performance; Vascular disease; Arterial disease; Joint kinetics

Peripheral artery disease (PAD) is associated with an altered gait profile that is present from the first step, before the onset of claudication pain. The altered gait profile found in patients with PAD presents as decreased muscle power contributions at the ankle, knee, and hip joints with marked weakness of the posterior compartment muscles of the hip and calf.[1-7]

Supervised walking exercise therapy (SET) has been shown to significantly increase pain-free walking time[8-16] and improve quality of life.[9,14,16,17] SET achieves the best results when the program lasts 4 months or longer with three sessions per week, lasting 30 minutes or more, at an intensity leading each patient to walk until near maximal pain.[8-16] SET has been found to achieve greater early functional status improvement for claudicating patients with aortoiliac disease compared with surgery and increases in maximum walking distances equal to or better than surgical revascularization, despite the fact that arterial insufficiency remains.[17]

Gait impairment at baseline confirms that mechanisms other than ischemia contribute to limb dysfunction in PAD. An improved understanding of how muscular strength and gait mechanics contribute to increased walking distances after SET can provide insight into why the SET intervention is effective. We hypothesized that SET for claudicating patients with PAD improves walking distances and quality of life in association with improved plantar flexor strength and gait biomechanics.

METHODS

The institutional review boards at Nebraska Western Iowa Veteran Affairs Medical Center and University of Nebraska Medical Center approved the study. All patients provided informed consent before study participation.

Participant inclusion and exclusion criteria

Patients with a positive history of exercise-limiting, chronic claudication were recruited from the vascular surgery clinics of the aforementioned institutions (Table I). The study screened patients for ambulation- limiting cardiac, pulmonary, neuromuscular, or musculoskeletal disease to ensure patients whose walking was limited by reasons other than claudication were not included in the study. All patients had no previous history of revascularization and had Fontaine stage II in the leg used for analysis (37 bilateral Fontaine stage II, 10 unilateral). Patient evaluation included resting ankle-brachial index (ABI; value of <0.9), detailed history, physical examination, and direct assessment and observation of the patients walking impairment by a vascular surgeon.

Exercise protocol

Patients participated in a 6-month, three times per week (72 session) SET program that followed the American College of Sports Medicine recommendations in concordance with previous studies that best produced increases in walking distances.[10,18] The program was conducted at the Center of Cardiovascular Disease Prevention and Rehabilitation of Creighton University Medical Center or associated rehabilitation centers in Nebraska and Western Iowa under a unified protocol. Each session included a 5-minute warm-up of mild walking and static stretching of upper and lower body muscles, 50 minutes of intermittent exercise on a treadmill, and

5 minutes of cool down activities similar to the warm-up. Exercise was initiated at a workload of 2 mph, or lower if desired by the patient, and 0% grade. Subjects walked until claudication pain reached a moderate to severe level and then rested until claudication pain subsided, at which point they would walk again, for up to 50 minutes. The SET program progressed after a patient could walk for 8 to 10 continuous minutes at the initial workload (2 mph, 0% grade) by increasing the grade by 1% to 2% or the speed by 0.5 mph as tolerated.

Experimental procedure and data collection

Patients were evaluated at the Biomechanics Research Building at the University of Nebraska at Omaha. The evaluations were performed before and after participation in SET. The patients completed tests in the following order: (1) the Walking Impairment Questionnaire (WIQ) and the Timed Up and Go test, (2) graded treadmill test,[19] (3) pain-free overground walking trials, (4) 6-minute walk test (6MWT),[20] (5) pain-induced over- ground walking trials, and (6) maximal isometric strength testing. During the overground walking trials, kinematics and kinetics were recorded as previously described[2,21] using a 12 high-speed infrared camera system (60 Hz, Motion Analysis Corp, Santa Rosa, Calif), and force platforms (600 Hz; AMTI, Watertown, Mass). Each patient walked across a 10-meter pathway contain- ing a force platform set level with the floor. Patients walked at a self-selected pace before (pain free) and after (pain) the onset of claudication pain. A mandatory rest of at least 1 minute was required between each pain-free walking trial to prevent the onset of claudication. Symptomatic claudication pain was induced by completing the 6MWT between pain free and pain induced trials. Once pain was induced patients immediately returned to the 10-meter pathway to perform the additional walking trials for the pain condition, with no rest given between trials. All patients experienced a moderate to severe level of pain in the leg used for analysis (more affected in bilateral claudicants; affected in unilateral claudicants). Five separate passes over the force platform per condition were collected for analysis.

ARTICLE HIGHLIGHTS

- Type of Research: Single-site, prospective non- randomized cohort
- Key Findings: Six months of supervised exercise therapy significantly improved self-perceived ambulatory limitation, walking distances, leg muscle strength, and gait biomechanics in 47 patients with peripheral artery disease.
- Take Home Message: Supervised exercise therapy concurrently increased walking performance and muscle strength, even though blood flow did not change. Supervised exercise therapy may be beneficial if used in combination with therapies that in- crease blood flow.

Measurements

Questionnaire. The WIQ is a measure of ambulatory limitation, measured by questionnaire that defines and detects changes in claudication symptoms over four subscores: pain, distance, speed, and stair climbing. Each question ranges in difficulty from 0 to 100, with 0 representing the most severe symptoms.[22,23]

Walking distance measures. Patients performed a standardized graded treadmill test; a protocol speed of 0.89 m/s (2.0 mph) that begins at 0% grade, and increases by 2% grade every 2 minutes.[19] The initial claudication distance was recorded as the first indication of claudication pain from the patient, and the total distance the patients were able to walk before stopping because of pain was recorded as the absolute claudicaion distance. For the 6MWT, two cones were placed 50 feet apart in the gait analysis laboratory. Patients were instructed to cover as much distance as possible during 6 minutes; the initial claudication distance and total distance walked were recorded.[20] The Timed Up and Go test was performed as a measure of function because it has been associated previously with balance and fall risk. Patients began seated in an armed chair and were instructed to stand up, walk until both feet crossed a piece of tape (3 m away), turn around, walk back and sit down.[24] ABI. The highest ABI value obtained during the patient's clinical evaluation was reported as the pre-SET value for the leg used in analysis. The post-SET ABI values reported are from the same leg as in the baseline evaluation and obtained in the patient's clinical post-SETevaluation.

Table I. Sample demographics

Clinical characteristic		
Male sex		97.8
Race		
Caucasian		78.72
African American		19.15
Hispanic	2.13	
Age		64.68 (6.74)
ABI range		0.16-0.89
Disease duration, months		55.7 (51.6)
Level of disease (%)		
Aortoiliac		14.9
Femoropopliteal		29.8
Multilevel smoking		55.3
Current		61.70
Former		36.17
Never	2.13	
Coronary artery disease		36.17
Obesity		21.28
Diabetes		25.53
Dyslipidemia		80.85
Hypertension		87.23

ABI, Ankle-brachial index.
Continuous variables are presented as mean (standard deviation). Categorical variables are presented as percentages.

Maximal strength. A 10-second, isometric strength measurement of the ankle plantar flexors was performed in a pain-free condition as previously described.[7] The area under the curve, which is representative of work performed, and peak torque/body weight were obtained from the resultant torque curves.

Biomechanics. Joint kinetics and kinematics were calculated for the sagittal plane during the stance phase of walking (from heel contact to toe off) from the overground walking trials. The stance phase was divided into the weight acceptance, single leg support, and pro- pulsion phases of stance. Ground reaction forces and joint angles, torques, and powers for the ankle, knee and hip were analyzed using custom MATLAB (Math- works, Inc, Natick, Mass) and Visual 3D (C-Motion, Inc, Germantown, Md) software for the pain free and pain conditions of patients with PAD before and after the SET. The dependent variables for joint angles calculated include the maximum and the minimum of each joint's flexion and extension angles. Ankle plantar flexion, knee flexion, and hip flexion occur during the weight acceptance phase of stance. Maximum knee extension takes place during single support phase of stance, and ankle dorsiflexion and hip extension occur during the propulsion phase of stance.

Joint torque is the net result of all forces acting around a joint. The peak values for extensor and flexor torques were identified for the ankle, knee, and hip joints. Ankle dorsiflexor torque, knee flexor torque, and hip flexor torque were identified in weight acceptance. Ankle plantar flexor torque, knee extensor torque, and hip extensor torque were identified in the propulsion phase of stance.

A joint's power is the product of the angular velocity and the net torque across a joint. It is the rate of work produced by contracting to move or stabilize a joint. Peak values were identified at the ankle, knee, and hip joints. In the weight acceptance phase, power absorption at the ankle and knee and generation at the hip were measured. In single support of stance, power absorption at the ankle and hip were assessed and power generation at the knee. Power generation at the ankle and hip and absorption at the knee were measured in propulsion.

A ground reaction force represents the force exerted on the ground by the subject's weight-bearing limb to which the ground exerts an equal and opposite force. The force is extracted into three orthogonal components (anterior-posterior, medial-lateral, and vertical). The magnitude and direction of the forces were collected using AMTI force platforms sampling at 600 Hz. Peak force values occurring in the weight acceptance phase include the impact of vertical force, braking force, braking impulse, and lateral force. Vertical force at midstance and medial force peaks occur during single support. The propulsion phase of stance includes peak push-off vertical force, propulsive force, and propulsive impulse discrete points.

Statistical analysis

Data were summarized in group means and standard deviations for all variables. One leg, the more symptomatic for each patient, was used for analysis. Paired *t*-tests were used to detect the effects of the SET on the questionnaire, walking distances, ABI, and maximal strength dependent variables. A two-factor, intervention (before and after SET) and condition (pain free vs pain), repeated measures analysis of variance was used for all biomechanics dependent variables ($P <$ .05; SPSS version 22 software, IBM, Armonk, NY).

Table II. Ankle-brachial index (*ABI*), walking distances, Walking Impairment Questionnaire (*WIQ*), and plantar flexor strength before and after supervised exercise therapy

Dependent variable	Before		After		*P* value
Body mass, kg	89.38	(18.7)	88.99	(18.9)	.460
ABI	0.56	(0.17)	0.52	(0.22)	.078
Timed Up and Go, seconds	11.14	(1.45)	10.84	(1.96)	.300
Distances, meters					
Initial claudication	99.20	(74.5)	272.73	(249.3)	<.001
Absolute claudication	317.23	(230.8)	668.22	(566.4)	<.001
Six-minute walk distance	340.42	(117.3)	333.11	(123.3)	.700
WIQ					
Pain	54.55	(21.99)	65.63	(22.63)	.008
Distance	29.80	(25.49)	39.75	(29.84)	.043
Walking speed	39.60	(24.91)	46.34	(26.19)	.127
Stair climbing	44.70	(29.04)	53.88	(27.54)	.045
Isometric plantar flexor strength (No.)					
Area	697.77	(264.03)	784.84	(234.25)	.012
Peak torque/BW	0.95	(0.34)	1.05	(0.35)	.007

BW, Body weight.
Values are presented as mean (standard deviation).
[a]Higher values for each of these categories suggest improvement.

Table III. Walking performance characteristics from the 6-minute walk test (*6MWT*)

Dependent variable	Before	After	*P* value
Initial claudication distance, 6MWT, meters	108.07 (68.8)[a]	176.21 (83.1)[a]	.046
Total no. of stops	15	14	ns
No. of patients who stopped	9 (n ¼ 9)	12 (n ¼ 5)	
Average stop time per 6 minutes	91.56 (47.4)	111.58 (53.9)	
Overground speed	2.21 (0.8)	2.2 (0.7)	
TM preferred speed	1.65 (0.6)	1.65 (0.6)	

Values are presented as mean (standard deviation).
[a]Forty patients experienced pain during the 6MWT and are included in the analysis. Six patients were excluded because they completed their 6MWT without any claudication pain.

RESULTS

Participants

In forty-seven patients with PAD, body mass and ABI did not significantly change between pre and post SET evaluations (Table II). Although the ABI decreased by 7.1%, this change was not significant (*P* ¼ .078).

Questionnaire

Three of the four subcategories of the WIQ (pain [20.3%; *P* ¼ .008], distance [26.7%; *P* ¼ .043], and stair climbing [20.5%; *P* ¼ .045]) showed significant increases after SET. Increased scores on the WIQ correspond with the patient indicating less difficulty walking owing to pain and the perception that they walk farther and are able to climb more flights of stairs on average after SET (Table II).

Walking distances

Both initial (175.9%; *P* < .001) and absolute (110.6%;*P* < .001) claudication distances on the standardized treadmill test significantly increased following SET (Table II). For the 6MWT, initial claudication distance (63.1%; *P* ¼ .046) improved but absolute claudication distance was not significantly improved (-2.1%; *P* ¼ .700; Table III). No effects were observed for the Timed Up and Go test (Table II).

The increases in the initial claudication time results were consistent for the treadmill and the 6MWT. However, because of the differences between the two walking tests, including the ability to rest and select speed in the 6-minute test, the total distance walked (6MWT) and the absolute claudication time (graded treadmill test) were not consistent. To investigate why the total distance achieved during the 6MWT did not improve, we calculated the number of patients who stopped, the duration of each stop, and the average speed walked during the 6 minutes (Table III). The average speed during the 6MWT was an estimate of overall speed because it did not account for the turn distance. Distance achieved was divided by the time each patient walked less time spent for a stop. The duration of the average stop time increased and so did the number of subjects who stopped (nonsignificant) after SET. Only 40 patients were included in this analysis because six subjects completed their 6MWT and reported that they did not experience claudication pain after SET.

Maximal isometric strength

The area under the curve (12.5%; *P* ¼ .012) and peak tor- que/body weight (10.5%; *P* ¼ .007) significantly increased after SET. This finding indicated that SET increased the capability of the ankle plantar flexors to produce work and generate maximal force during an isometric contraction (Table II).

Table IV. Dependent variables from the weight acceptance phase of stance[a]

Joint and/or variable	Pain free				Pain				Pi	Pc
	Before		After		Before		After			
Ankle										
Dorsiflexion angle,	12.89	(4.7)	13.28	(4.7)	14.15	(4.7)	14.21	(4.9)	.677	<.001
Dorsiflexor torque, N*m	-0.25	(0.1)	-0.26	(0.1)	-0.24	(0.1)	-0.23	(0.1)	.885	.023
Power absorption, Watts	-0.48	(0.2)	-0.51	(0.3)	-0.48	(0.3)	-0.49	(0.3)	.514	.554
Knee										
Flexion angle,	2.89	(5.0)	2.41	(5.1)	2.35	(5.1)	1.52	(5.5)	.265	.003
Extensor torque, N*m	0.53	(0.3)	0.56	(0.3)	0.56	(0.3)	0.56	(0.3)	.695	.404
Power absorption, Watts	-0.66	(0.5)	-0.74	(0.5)	-0.81	(0.8)	-0.75	(0.5)	.861	.089
Hip										
Flexion angle,	-2.86	(4.9)	-3.90	(5.8)	-2.00	(5.2)	-3.07	(6.0)	.281	<.001
Extensor torque, N*m	0.6 7	(0.3)	0.81	(0.2)	0.69	(0.4)	0.79	(0.3)	.012	.963
Power generation, Watts	0.4	(0.4)	0.44	(0.4)	0.42	(0.4)	0.43	(0.4)	.682	.988
Peak forces, body weight										
Vertical impact	1.09	(0.1)	1.12	(0.15)	1.09	(0.12)	1.1	(0.12)	.253	.529
Braking force	-0.15	(0.04)	-0.16	(0.05)	-0.16	(0.05)	-0.16	(0.05)	.393	.219
Braking impulse, N*s/kg	-0.032	(0.01)	-0.030	(0.01)	-0.031	(0.01)	-0.029	(0.01)	.559	.041
Lateral force	-0.038	(0.02)	-0.042	(0.02)	-0.041	(0.02)	-0.046	(0.02)	.021	<.001

Pc, Condition (pain free/pain); *Pi,* intervention (pre/post supervised exercise therapy).
Values are presented as mean (standard deviation). Boldface entries indicate statistical significance.
[a]To support the trunk at heel strike, the hip extensors, primarily gluteus maximum and the hamstrings,[25] concentrically contract to extend the hip, while the extensors at the knee eccentrically contract to permit slight flexion at the knee. The hip extensors stabilize the posture of the trunk by preventing it from flexing forward under the influence of a large posterior reaction force at the hip, which helps the knee extensors to eccentrically contract and prevent collapse at the knee.[26] A positive torque value represents a flexor response and a negative torque value indicates an extensor response. Positive power represents energy generation and is associated with concentric muscle contraction whereas negative power indicates energy absorption and is associated with eccentric muscular contraction.

Biomechanics, intervention factor

Weight acceptance. Patients significantly increased hip extensor torque (17.6%; *P* ¼ .012) and peak lateral force generation (11.4%; *P* ¼ .021) during the weight acceptance phase of stance after SET (Table IV).

Single-limb support. The increase in peak lateral force during weight acceptance resulted in a significant increase in ankle power absorption (7.5%; *P* ¼ .023) during single-limb support following SET. There were no other changes after SET for the single limb support (Table V).

Propulsion. Patients significantly increased power generation at the ankle (14.5%; *P* ¼ .003) and hip (14.3%; *P* ¼ .003) during the propulsion phase of gait (Table VI) and these improvements translated to a significant increase in peak propulsive force (12.1%; *P* ¼ .006). Therefore, after SET, patients were better able to propel themselves forward during terminal stance.

Biomechanics, condition factor

Early stance. A significant effect of condition was found for ankle angle (-8.3%; *P* < .001) and torque (-7.8%; *P* ¼ .023), knee angle (-27.0%; *P* ¼ .030), and hip angle (-25.0%; *P* > .001). At the ankle, the dorsiflexion angle increased and torque decreased in magnitude during pain conditions. Both knee and hip extension angles decreased in magnitude during pain. Main effects were also observed for peak forces in the braking impulse (-3.2%; *P* ¼ .041) and lateral force (-8.8%; *P* < .001), which decreased and increased in magnitude during pain, respectively.

Midstance. A main effect was found for ankle power absorption (-7.5%; *P* < .001), where absorption at the ankle increased when patients were in the pain condition.

Late stance. The main effects at the ankle included plantar flexion angle (-10.5%; *P* < .001), plantar flexor torque (-6.3%; *P* < .001) and power generation(-12.2%; *P* < .001), knee power absorption (-9.1%; *P* ¼ .017), hip extensor torque (-4.4%; *P* ¼ .046) and power generation (-5.2%; *P* ¼ .039), and peak push- off vertical force (-2.4%; *P* < .001) and propulsive force (-5.6%; *P* ¼ .002). Ankle plantar flexion angle increased during pain conditions, whereas all other effects decreased in magnitude during pain

Table V. Dependent variables from the single leg support phase of stance[a]

Joint and/or variables	Pain free				Pain				Pi	Pc
	Before		After		Before		After			
Power, Watts										
Ankle absorption	-0.83	(0.3)	-0.9	(0.3)	-0.9	(0.3)	-0.96	(0.3)	.023	<.001
Knee generation	0.32	(0.3)	0.37	(0.4)	0.4	(0.3)	0.35	(0.2)	.937	.332
Hip absorption	-0.59	(0.3)	-0.61	(0.3)	-0.61	(0.4)	-0.61	(0.3)	.804	.485
Peak forces, body weight										
Vertical midstance	0.77	(0.07)	0.79	(0.11)	0.79	(0.09)	0.79	(0.11)	.516	.118
Medial	0.062	(0.002)	0.066	(0.002)	0.061	(0.002)	0.063	(0.002)	.128	.292

Pc, Condition; *Pi,* intervention.
Values are presented as mean (standard deviation). Boldface entries indicate statistical significance.
[a]During single-leg support, the plantar flexors contract isometrically and produce a net effect of reaction forces to the leg and trunk, which provide support and enable subsequent transfer of body mass in forward progression.

Table VI. Dependent variables from the propulsion phase of stance[a]

Joint and/or variable	Pain free				Pain				Pi	Pc
	Before		After		Before		After			
Ankle										
Plantar flexion angle,	-7.34	(4.6)	-7.38	(4.7)	-7.95	(4.5)	-8.31	(4.4)	.735	<.001
Plantar flexor torque, N*m	1.32	(0.2)	1.37	(0.3)	1.24	(0.2)	1.28	(0.2)	.148	<.001
Power generation, Watts	2.15	(0.5)	2.43	(0.6)	1.86	(0.7)	2.16	(0.7)	.003	<.001
Knee										
Flexion angle,	14.38	(5.7)	14.14	(6.5)	14.29	(5.6)	13.81	(6.8)	.573	.476
Flexor torque, N*m	-0.18	(0.2)	-0.2	(0.2)	-0.18	(0.2)	-0.2	(0.2)	.656	.921
Power absorption, Watts	-0.8	(0.3)	-0.85	(0.4)	-0.75	(0.4)	-0.75	(0.3)	.705	.017
Hip										
Extension angle,	34.04	(6.2)	34.12	(7.0)	34.54	(6.9)	34.55	(7.5)	.950	.055
Extensor torque, N*m	-0.79	(0.2)	-0.8	(0.3)	-0.76	(0.3)	-0.76	(0.3)	.946	.046
Power generation, Watts	0.71	(0.2)	0.83	(0.2)	0.69	(0.2)	0.77	(0.2)	.003	.039
Peak forces, body weight										
Vertical push-off	1.03	(0.07)	1.07	(0.14)	1.01	(0.07)	1.04	(0.13)	.130	<.001
Propulsive	0.17	(0.03)	0.19	(0.05)	0.16	(0.04)	0.18	(0.04)	.006	.002
Propulsive impulse, N*s/kg	0.031	(0.01)	0.033	(0.02)	0.031	(0.01)	0.033	(0.01)	.412	.944

Pc, Condition; *Pi,* intervention.
Values are presented as mean (standard deviation). Boldface entries indicate statistical significance.
[a]The primary muscles contributing to propulsion are the plantar flexors, where the gastrocnemius delivers energy to the leg and the soleus to the trunk for support and forward progression.[27] The hip pattern during propulsion includes contribution by the flexors and hamstrings to achieve a greater energy level of the thigh leading into the swing phase of gait.

DISCUSSION

This study characterized and provided an in-depth look at limb function in patients with intermittent claudication before and 6 months after participation in SET as a first line of treatment, before and after the onset of claudication. This study also evaluated whether gait parameters improved in conjunction with questionnaire results, walking distances, ABI, and ankle strength after the intervention. Other studies have used either joint kinematics alone[28] or kinematics and partial peak forces.[29] The current study provided a more comprehensive functional evaluation of the effects of a standardized SET to increase walking distances in patients with PAD. It also included an evaluation of the primary deficits previously identified as key factors underlying the gait adaptions in claudicating patients with PAD.[2-7,30]

Effect of intervention

Our hypothesis was partially supported; weakness in the posterior calf muscles was a consistent and key factor underlying the gait abnormalities patients with PAD experienced before pain onset. Improvements in isometric plantar flexion strength and ankle power during the single support and propulsion phases of gait before and after the onset of claudication pain reflected important improvements. Our data also demonstrated significant improvements in absolute walking distances, pain-free walking time, and questionnaire-based assessment of claudication symptoms, which are in agreement and consistent with preexisting literature in terms of percentage improvements.[8-12,14,16,17,31-33]

Weight acceptance. Before therapy, patients with PAD demonstrated a decreased ability of the hip and knee extensors to perform during weight acceptance and to control forward momentum compared with healthy controls. Our findings in patients with PAD after SET demonstrated increased torque development by the hip extensors. These changes represented an improvement in gait after SET, or a gait pattern in PAD more similar to the gait of healthy participants.[2,4,30] At the ankle during weight acceptance, the dorsiflexors eccentrically control the movement of the foot until it makes complete contact with the ground. Immediately after heel strike and during the downward movement of the foot is when a brief (2%-8%) lateral ground reaction force is produced, and is thought to be directed by the gluteus maximus, adductors of the thigh, and vasti muscles.[34] Patients with PAD demonstrate a foot-drop, or impaired control of the downward motion of the foot after heel strike.[3] Although no improvements were found at the level of the ankle dorsiflexors in this study, an increased lateral ground reaction force after SET was found. This finding reflected improved synchronization of the ipsilateral adductors at heel strike to accept weight transfer from the contralateral leg, and to permit greater control in the upcoming phases of stance. Previously, we found this force to be decreased as a pre- compensatory step to increased medial force (greater than healthy controls), to allow for a wider step and decreased single limb support time.[4] Although the change in lateral ground reaction force is minimal, it seems that SET may have promoted better coordination and reduced a common compensatory action in patients with PAD.

Single-leg support. Our data demonstrated an in- crease in ankle power absorption, which indicated improved energy delivery to the leg and trunk by the plantar flexors during this phase of stance. We have not previously identified this variable to be different from healthy controls at baseline. This adaptation after SET could be the result of increased muscle capacity and the ability to use the energy generated during this phase. Propulsion. Our data demonstrated significant improvements in ankle and hip power generation that translated to increased propulsive ground reaction force. More specifically, the plantar flexors improved their contribution to forward progression and support as did the hip flexors in their assistive role in forward trunk acceleration.

Effect of condition

The onset of claudication affected biomechanics throughout stance before and after SET. These differences corresponded with a worsening gait or a gait pattern that moved further from healthy individuals compared with pain-free gait.[2,4,5] In single-leg support, ankle power absorption increased in magnitude during claudication. In propulsion, ankle plantar flexor angle increased, and torque and power decreased. Knee flexor power decreased, and hip flexor moment and power decreased. The peak propulsive and vertical push-off forces also decreased. Overall, the propulsion phase continued to be the most affected by the onset of claudication, which could be due to purposeful adjustments by the patient to minimize the use of and pain felt in the more symptomatic limb.

Improvements in walking distances but not hemodynamics

Significant improvements in initial and absolute claudication distances were observed on the graded treadmill protocol after SET. Parallel improvements were not observed in maximum overground walking distances, measured by the 6MWT, or in resting ABI measurements. The improvements in treadmill distances and lack thereof in resting ABI are in agreement with previous literature.[25] Average ABI values decreased numerically from 0.56 to 0.52 after SET, which was not significant. Many previous SET studies do not report the post-SET ABI.[26] One systematic review of randomized controlled trials evaluating the evidence for the effect of exercise on lower limb hemodynamic measures report no significant change in the resting ABI after SET in 28 of 29 trials. Our study was not designed or powered to explore a potential change in the resting ABI, but other studies evaluating the natural progression of ABIs among patients with PAD report a decrease of .004 to .020 per year as the expected average change.[35-37] In these studies, degree of progressive decrease in the ABI is found to be associated with current smoking status, requirement for an intervention, older age, diabetes, and the severity of the presenting symptoms. The SET protocol was similar to the maximal treadmill test performed and may help to explain why improvements in the 6-minute walk distance did not occur. Significant discussion exists in the literature regarding the pros and cons of each type of maximum walking test, and this study further illustrates the points that each test assesses slightly different outcomes (peak vs daily living walking performance).

Our analysis of the findings of the 6MWT and graded treadmill test suggested that SET improved pain tolerance and walking endurance but did not improve self- selected average walking speed. The increased pain tolerance was seen in increased claudication onset time during both 6-minute walk (self-paced) and the graded treadmill test (controlled intensity) and the higher score for the pain category on the WIQ. Improvement in endurance was demonstrated by increased peak walking time during the graded treadmill test, improved ankle and hip power generation during pro- pulsion, improved peak torque and total work during maximum plantar flexion strength testing, and the higher scores for WIQ distance. Our analysis of average walking speed during the 6MWT demonstrated that SET did not produce a change in the self-selected speed of our patients. It is possible that, if the instructions on the 6MWT asked patients to maintain speed and not to stop (similar to inherent demands of the graded tread- mill test, which controls the intensity), total walking distance would increase in a way that is parallel to that see with the graded treadmill test. Instead, the patients seemed to adapt by slowing down and/or resting, which was likely an attempt to avoid or decrease pain.

A limitation of this study is the modest sample size; additional participants could strengthen our findings. Our data, however, show that SET produces partial resto- ration of impaired limb function of patients with PAD despite fixed arterial occlusive disease. The biological pathways by which exercise improves walking performance were not evaluated in the present work, and their examination has been proposed as a top priority in a recent scientific statement from the American Heart As- sociation under the discussion on the future of investigations of exercise intervention in patients with PAD.[38]

Overall, the biomechanical improvements found during weight acceptance and propulsion were in line with the increased walking distances. Specifically, increased activation of the hip extensors helped to maintain momentum and walking speed after heel strike. In particular, greater activation of the ankle during propulsion led to a more efficient gait after SET. Overall, these improvements translated to an increased capacity on the graded treadmill test. These increases were not seen on the 6-minute walk (self-paced) test, which means that subjects may have had a greater maximal capacity owing to SET, but lingering impairments in blood flow delivery and the structure and function of leg muscles led subjects to choose to walk slower and/ or rest during the self-paced test.

CONCLUSIONS

Six months of SET produced significant increases in the treadmill walking distances of patients with claudication. These increases were consistent with concurrent improvements in gait biomechanics at the level of the ankle and the hip. SET produced strengthening of the hip extensor and the ankle plantar flexor muscles and this strengthening appears to be the main mechanism producing the improvements of the walking ability of patients with claudication.

AUTHOR CONTRIBUTIONS

Conception and design: IP, JJ, GC, MW, SM
Analysis and interpretation: MS, IP, JJ, GC, MW, BS, SM Data collection: MS, IP, HD, GC, MW, BS, SM
Writing the article: MS, IP, SM
Critical revision of the article: IP, JJ, HD, GC, MW, BS, SM Final approval of the article: MS, IP, JJ, HD, GC, MW, BS, SM Statistical analysis: MS, IP
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