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Peripheral arterial disease affects kinematics during walking

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Peripheral Arterial Disease affects Kinematics during Walking

ABSTRACT

Objective: Claudication is the most common manifestation of peripheral arterial disease (PAD) producing significant ambulatory compromise. The purpose of this study was to use advanced biomechanical analysis to characterize the kinematic ambulatory pattern of claudicating patients. We hypothesized that compared to control subjects, claudicating patients have altered kinematic gait patterns that can be fully characterized utilizing advanced biomechanical analysis.

Methods: The study examined fourteen PAD patients (age: 58 +/- 3.4 years; weight: 80.99 +/- 15.64 kg) with clinically diagnosed femoro-popliteal occlusive disease (Ankle Brachial Index (ABI): 0.56 +/- 0.03, range 0.45-0.65) and five healthy controls (age: 53 +/- 3.4 years; weight: 87.38 +/- 12.75 kg; ABI $\geq$ 1). Kinematic parameters (hip, knee and ankle joint angles in the sagittal plane) were evaluated during gait in patients before and after the onset of claudication pain and compared to healthy controls. Joint angles were calculated during stance time. Dependent variables were assessed (maximum and minimum flexion and extension angles and ranges of motion) and mean ensemble curves were generated. Time to occurrence of the discrete variables was also identified.

Results: Significantly greater ankle plantar flexion in early stance and ankle range of motion during stance was observed in PAD patients ($P<0.05$). Time to maximum ankle plantarflexion was shorter and time to maximum ankle dorsiflexion was longer in PAD patients ($P<0.05$). These differences were noted when comparing PAD patients prior to and after the onset of claudication with healthy controls. The analysis of the kinematic parameters of the knee and the hip joints revealed no significant differences between PAD patients and controls.

Conclusion: PAD patients with claudication demonstrate significant gait alterations in the ankle joint that are present prior to the onset of claudication pain. In contrast, the joint motion of the hip and knee did not differ in PAD patients when compared to controls. Further research is needed

to verify our findings and assess the impact of more proximal disease in PAD patients as well as the effect of revascularization on joint kinematics.

KEYWORDS: Claudication, Gait, Kinematics, Peripheral Arterial Disease, Biomechanics

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INTRODUCTION

Peripheral arterial disease (PAD) of the lower extremities is a manifestation of atherosclerosis, affecting 20%-30% of older patients in general medical practices [1,2] and up to 12 million people in the United States population.[3,4] Intermittent claudication (IC), defined as lower extremity pain that causes the patient to stop walking and resolves within few minutes of rest, is considered the classic symptom of PAD. Recently IC has been identified as an ambulatory disorder. This is supported by studies demonstrating PAD patients to have lower daily physical activity[5], reduced strength in lower extremities[6], worse self-perceived ambulatory function[7], lower health related quality of life[8], impaired balance and higher prevalence of falling[9].

The characterization of the gait of patients with IC until recently has been limited to the measurement of simple temporal and spatial parameters of the patients' walking performance. Such evaluations have documented that PAD patients have decreased step length, cadence, walking speed and increased stance time[10,11]These measures suggest the presence of ambulation abnormalities in claudicating patients; however they provide limited insight into the specific site and mechanisms producing the abnormal gait.

Biomechanical analysis, in contrast to the previously used rudimentary measurements mentioned above, represents an important diagnostic tool with the ability to provide detailed and accurate quantitative gait analysis. Furthermore, biomechanical evaluation is common practice is several other medical domains (i.e. orthopedics, pediatrics, neurology, etc) and has been useful in both research and clinical settings for directing treatment in varying pathologies as well as in outcome evaluation of the results of such treatments[12-15]. In contrast to the progress made in other fields where advanced biomechanics has been implemented, very little has been done to provide an in depth analysis of the underlying biomechanical gait abnormalities produced by PAD[16,17].

The purpose of the current study was to determine the gait of patients with symptomatic PAD before and after the onset of claudication utilizing advanced biomechanical analysis. We hypothesized that the lower extremities of PAD patients have altered joint displacement compared

to control subjects both before and after the onset of claudication, and that biomechanical kinematic analysis represents a diagnostic tool with appropriate sensitivity to detect subtle differences in a subject's gait. The current kinematic study, which focuses on the lower extremity joints' angular displacement independently of the generating forces, complements the kinetic analysis previously described by our group [18] which evaluated the forces exerted by the subjects weight-bearing limb on the ground. Our work seeks to further enhance our understanding of the abnormal gait in subjects with PAD, thus providing the foundation for the development of new rehabilitation strategies and the quantification of treatment outcomes for patients with symptomatic PAD.

METHODS

Subjects

Institutional Review Board approval was obtained prior to initiation of the study and all subjects provided informed consent. Patients with clinically diagnosed PAD presenting with classic symptomatic claudication were recruited from our vascular surgery clinics. Selected patients were free of any associated co-morbidities limiting or altering their gait. Specifically, subjects were excluded if they had recent myocardial infarction or ambulation-limiting heart failure, angina or pulmonary disease. Additionally, subjects were excluded if they had gait altering neurological or musculoskeletal disease such as paresis, sciatica, arthritis, diabetic neuropathy or arthropathy. History and physical examination of the subjects evaluated was performed by board certified vascular surgeons (JJ, IP). Lower extremity arterial disease was verified by classic clinical symptoms confirmed utilizing noninvasive testing (ankle-brachial indexes < 0.9) and the level of disease identified with the aid of noninvasive vascular examination complemented by computerized tomography, magnetic resonance or invasive angiography. Based on this assessment, limbs with occlusive disease and typical Rose claudication symptoms[19] were established as "claudicating limbs" and selected for biomechanical analysis.

Control subjects were recruited from the community. Detailed history and physical examination performed by vascular surgeons documented absence of PAD and co-morbidities as described for PAD patients. Absence of PAD was confirmed by noninvasive testing (ankle-brachial indexes) and absence of pain during ambulation. Each leg of these individuals was used as "control limb". To eliminate variability in gait due to shoes, all subjects wore the same standard laboratory shoes (Cross Trekkers, Payless Shoes, Topeka, KS).

Lower extremity kinematics

Upon arrival in the laboratory, patients were prepared for data collection. Height, weight, body mass index, age and anthropometric measurements were obtained. Reflective markers were placed at specific anatomical locations of each subject's lower limb utilizing the systems used by Vaughan[20] and Nigg[21] and as described in Figure 1. The subjects' lower extremity three-dimensional kinematics was acquired with a high speed analog video Peak Performance system at 60Hz (Peak Performance Technologies, Englewood, CO). Marker identification was conducted using the Peak Motus (Vicon-Peak Performance Technologies, Inc.) software. The exported marker data was scaled and smoothed using a Butterworth low-pass filter with a selective cut-off algorithm according to Jackson[22]. The cut-off values used were 7-14 Hz. This analysis was performed using custom software in Matlab (Mathworks Inc. Natick, Mass), where the exported data was also converted to unit vectors for each local reference frame. Anthropometric measurements were combined with three-dimensional marker data from the anatomical position calibration trial (see below) to provide positions of the joint centers and define anatomical axes of joint rotations [20]. The positions of the reflective markers during the movement provided the three-dimensional joint angles and were determined through triangulation of the position of the markers.

Prior to the walking trials, patients stood in the calibration device for five seconds while kinematic video was collected with each leg in view of the cameras. The standing calibration trial provided an anatomical reference position. The calculation of three-dimensional lower extremity segment orientations and relevant joint angles was referred to this position. Kinematic data was

collected during the stance phase of walking (from heel contact to toe off). Initially five walking trials were acquired from each PAD subject without pain present and represented the "pain free" condition (PAD-PF). During this condition the patients were required to rest in a chair for at least five minutes before, and between trials to ensure pain free measurements. After PAD patients completed the pain free walking trials, claudication pain was induced. This was accomplished by having patients walk on a treadmill at a 10% grade at 0.67 m/s until claudication was induced (usually patients become symptomatic after 1 to 3 minutes on the treadmill) and then for approximately 45 additional seconds. Patients returned to the walkway immediately where five more walking trials were performed without any resting between the trials. Claudication pain was present throughout these trials and represented the claudication or "pain" condition of the PAD patients (PAD-P). Data from the healthy controls was collected following the protocol used to obtain the pain free data from the PAD patients, with claudication data not obtained due to lack of PAD in these individuals.

Data Analysis

Joint angles from the hip, knee and ankle were analyzed for the two conditions of the PAD patients and for the controls. Dependent variables calculated were the range of motion, the maximum and the minimum of the joints' flexion and extension angles. All kinematic parameter data files were normalized to 100 points for the stance phase using a cubic spline routine to enable mean ensemble curves to be derived for each condition of each subject. All normalization occurred after maximums and minimums were determined to ensure that the normalization did not distort these values[23,24].

Statistical analysis

Statistical analysis was performed using SPSS (version 15; SPSS Inc, Chicago, Ili). Subject and group means were calculated and inferential statistics were used to compare the different groups. Independent t-tests were used to compare mean values of PAD patients (PAD-PF and PAD-

P) to healthy controls. Paired t-tests were used to compare PAD-PF to the PAD-P condition. Significance was set at 0.05.

RESULTS

Demographics

Fourteen PAD patients (age: 58 +/- 3.4 years; weight: 80.99 +/- 15.64 kg; height: 172.12 +/- 6.78 cm) with clinically diagnosed femoro-popliteal occlusive disease (Ankle Brachial Index (ABI): 0.56 +/- 0.03, range 0.45-0.65) were recruited. All patients had classic Rose claudication or Rutherford category 2 symptoms [25]. Eighty percent of the patients were hypertensive, 70% were smokers, 60% had dyslipidemia, and 30% were obese (BMI>30 kg/m^2). All patients were treatment naive. From these fourteen patients, a total of 20 symptomatic PAD legs were included for kinematic analysis. Five control subjects with absence of PAD and absence of any ambulatory disability (age: 53 +/- 3.4 years; weight: 87.38 +/- 12.75 kg; height: 178.78 +/- 4.32 cm and ABI = 1.00 or greater) were evaluated. Two subjects had dyslipidemia and one had hypertension. From these subjects both legs were utilized providing a total of 10 legs. Body mass index values were 28.5 +/- 0.98 for PAD patients and 27.3 +/- 1.5 for control subjects. Subjects were well-matched regarding age and body mass index with no significant differences noted between groups ($p < 0.05$).

Kinematic Analysis

At the level of the ankle, significant differences were noted between PAD patients and control subjects (Table 1). Increased minimum (negative values) ankle plantar flexion during the initial stance phase and increased range of motion (ROM) throughout the stance phase was observed in claudicants when compared to controls in both PAD-PF and PAD-P conditions (Table 1; Figure 2). Since no differences were found for maximum (positive values) ankle dorsiflexion (Table 1), these results are reflected as a deeper “valley” on the ankle mean ensemble curve for PAD patients when compared with the control subjects (Figure 2). The time to minimum plantar

flexion and maximal dorsiflexion of the ankle joint during the stance phase was significantly altered when comparing PAD-P to control subjects. The PAD-P patient reached minimum ankle plantar flexion faster and maximum dorsiflexion later than the control subject (Table 2). When analyzing the effect of claudication on joint motion at the knee and hip, no significant differences were noted in joint angles.

When analyzing the effect of claudication pain by comparing the PAD-PF to PAD-P conditions, there were no significant differences noted in joint motion at each joint level or in the timing of specific points within the gait cycle. These results are also reflected in the mean ensemble curves since the lines for PAD-P and PAD-PF are overlapping throughout stance (Figure 2).

DISCUSSION

Our data demonstrated that patients with clinically diagnosed femoro-popliteal PAD have significant ankle motion alterations with abnormal ankle joint kinematics. During the stance phase of the gait cycle, the PAD patients demonstrated rapid foot plantar flexion after initial heel strike coupled with a significant increase in ankle plantar flexion. The increase in ankle plantar flexion with subsequent normal maximal dorsiflexion resulted in PAD patients having a significantly increased ankle range of motion. This phenomenon was present both before and after the onset of claudication pain. Based on our kinematic analysis, PAD patients have what appears to be “foot drop” upon heel touchdown. The etiology of this finding is currently unknown but is likely secondary to nerve damage and muscle weakness from chronic ischemia [28,29,33]. This could result in poor eccentric motor control from the foot dorsiflexors (anterior and lateral compartment leg muscles) in combination with suboptimal plantar flexor function (posterior compartment muscles). Taken together, these findings represent either a compensatory mechanism to maintain stability due to inherent neuromuscular weakness of the lower limb or alternatively an adaptation to altered neuromuscular function due to PAD. Consistent with any dysfunctional gait, PAD patients have a deviation from normal walking parameters that results in an increased work requirement and energy

cost. [39,40]. Future research should expand on the analysis of joint moments at the level of the ankle to confirm the location of motor dysfunction and the contribution of nerve dysfunction to the gait abnormality.

In contrast to the findings at the ankle in our current cohort of patients, there was a lack of changes in the hip and knee in both flexion and extension in both conditions for PAD and control patients. This result could be due to the fact that the patients in the current study had clinically diagnosed femoro-popliteal occlusive disease with classic Rose claudication with absence of thigh and buttock claudication. One could argue that only the lower leg musculature was involved in the ischemic process and therefore the proximal muscles were spared. Further studies will be necessary to delineate the full spectrum of ambulatory compromise in patients with isolated aorto-iliac occlusive disease and multi-level disease.

An important finding in our study is that PAD patients had evidence of significant ambulatory abnormalities even when not experiencing any claudication pain. There is likely also a further alteration in gait function with claudication pain as the patients in our series showed a trend for increased differences of gait parameters compared to controls such as ankle plantar flexion and range of motion after onset of claudication pain but the differences did not reach statistical significance.. These results confirm unequivocally the presence of a significantly altered and dysfunctional gait prior to the onset of claudication pain despite what appears to be “normal” gait by simple visual analysis. These findings we believe reflect a baseline lower extremity dysfunction in PAD patients with origins at the cellular level[26,27]. The abnormalities contributing to the baseline gait dysfunction include axonal nerve loss [28,29] and mitochondrial dysfunction[30-35] both of which could account for the underlying gait dysfunction found in PAD patients from the first step during ambulation. Ischemia superimposed on underlying neuromuscular dysfunction would then result in variably worsening gait as seen in our previous kinetic analysis [18].

Previous studies have reported kinematic analysis of elderly individuals, showing deceased ankle plantar flexion when compared with younger controls[36]. The results of the kinematic analysis

of our control patients are similar to those reported on the literature on healthy elderly subjects. In contrast, little data exists to document the kinematic analysis of patients with PAD. Previous literature utilized simple visual observations in PAD patients to analyze differences in gait parameters with conflicting results. A recent study by Crowther et al has documented the effect of PAD on gait biomechanical parameters, only before the onset of claudication pain[17]. Although difficult to compare to our study due to differing methodologies, this study also found differences at the ankle. In contrast to our results, they found differences in the knee ROM and hip extension. Our methodology only included patients with clinically diagnosed femoro-popliteal disease and focused the analysis of the joints to the stance phase of the gait cycle. Crowther et al did not specify a level of disease among the patients and included the swing phase in the analysis of the joints' ranges of motion. Another factor contributing to the precision of our results is the capability of our lab to provide a three-dimensional analysis given the number of cameras used, Crowther et al, in contrast, utilized a two-dimensional kinematic analysis of the sagittal plane, which is vulnerable to perspective error [37,38]. When comparing the ankle curves of both studies, Crowther et al demonstrated an increased plantar flexion in the control patients in the swing phase only. Our results, similar to Crowther et al, showed increased plantar flexion of the controls at the end of stance phase. In contrast to Crowther's report, we detected an increased plantar flexion of the PAD patients in the stance phase. Both studies document similar alterations at the ankle level with the differences secondary to methodology and length of gait cycle analyzed. Both studies confirm however the significant ankle dysfunction in the PAD patient and providing a start point to elucidate the underlying joint biomechanical abnormalities found in patients with symptomatic PAD.

CONCLUSION

Kinematic gait analysis demonstrates that patients with clinically diagnosed femoropopliteal disease have altered ankle plantar flexion present before and after the onset of claudication pain

compared to control subjects. Our data in conjunction with previous biomechanical analysis confirm that patients with symptomatic PAD have an underlying ambulatory abnormality present even prior to onset of claudication pain. Further biomechanical evaluation of PAD patients should focus on the impact of disease level on gait dysfunction and evaluation of joint moments and powers to identify the specific muscular deficits produced by PAD. Our results provide evidence for the utilization of advanced biomechanical analysis to identify the unique gait abnormalities in PAD patients, thus providing a powerful research tool for objective analysis of medical and surgical PAD treatment and rehabilitation therapy.

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Table 1

	Control (degrees)	PAD-PF (degrees)	p†	PAD-P (degrees)	p‡	p⌋
Hip Flex	22.824±3.334	23.094±4.751	NS	22.9388±5.009	NS	NS
Hip Ext	-20.225±3.605	-18.773±6.427	NS	-19.1206±5.390	NS	NS
Hip ROM	43.050±1.915	41.870±6.542	NS	42.060±5.846	NS	NS
Knee Flex	19.021±4.849	18.065±6.261	NS	17.525±6.741	NS	NS
Knee Ext	1.247±4.246	1.102±5.504	NS	0.842±5.677	NS	NS
Knee ROM	17.773±3.649	16.962±5.493	NS	16.684±4.688	NS	NS
Ankle Plantarflex	-3.458±3.427	-7.596±2.520	0.0001	-8.368±2.764	0.0004	NS
Ankle Dorsiflex	14.500±2.407	16.539±4.767	NS	16.254±4.470	NS	NS
Ankle ROM	17.962±4.531	24.1371±4.934	0.003	24.621±4.363	0.001	NS

Table 2

	Control (degrees)	PAD-PF (degrees)	p†	PAD-P (degrees)	p‡	p¶
Hip Flex time	13.919±6.761	13.523±7.627	NS	12.209±5.801	NS	NS
Hip Ext time	86.439±1.349	86.180±3.292	NS	87.241±2.244	NS	NS
Knee Flext time	28.447±3.783	26.838±6.065	NS	26.851±6.383	NS	NS
Knee Ext time	68.87±1.949	68.268±5.186	NS	67.296±5.960	NS	NS
Ankle Plantarflex time	17.087±1.800	16.224±2.526	NS	15.710±1.233	0.026	NS
Ankle Dorsiflex time	72.788±11.327	78.264±7.134	NS	79.966±5.815	0.038	NS

Figure 1

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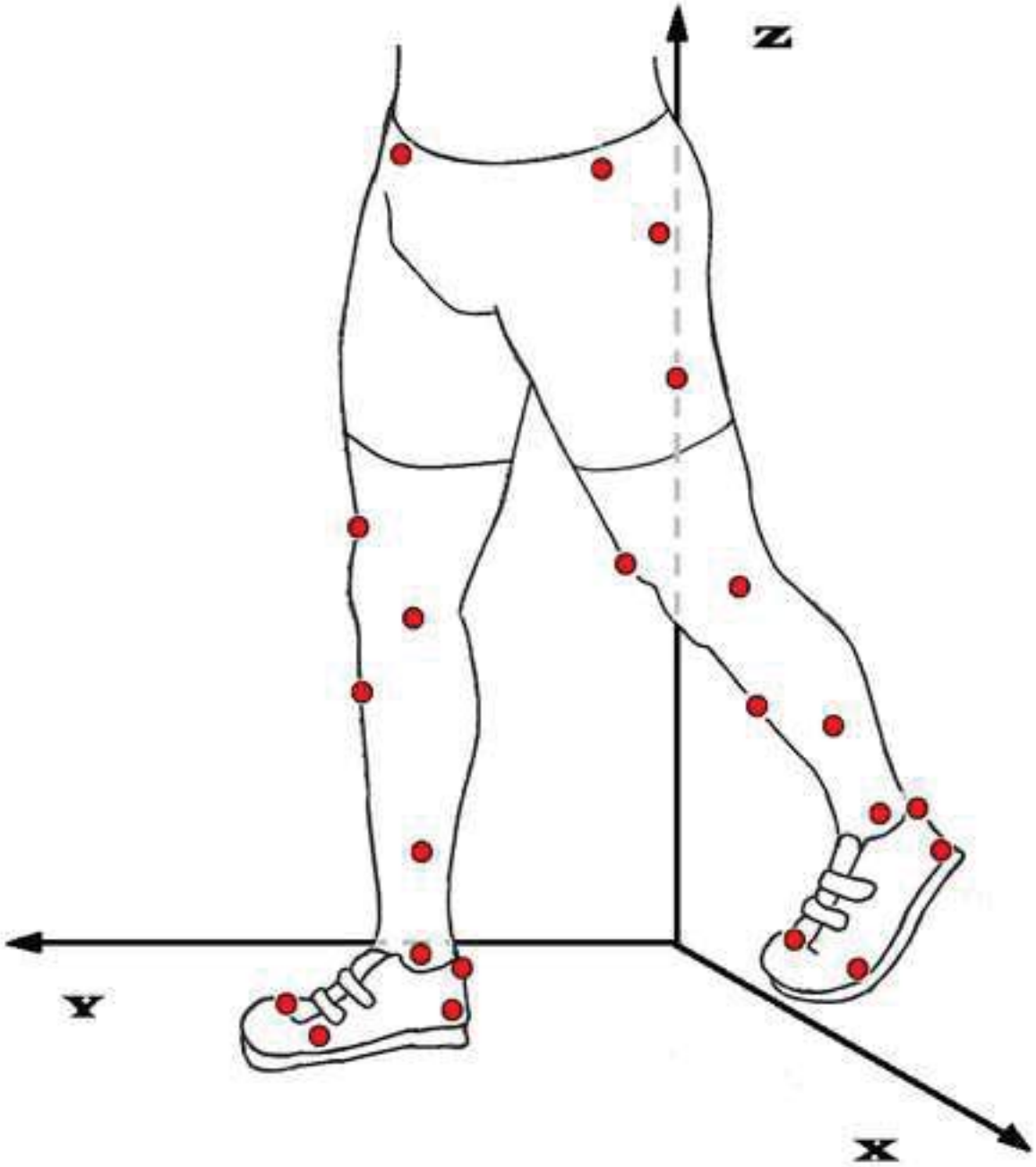

Figure (2

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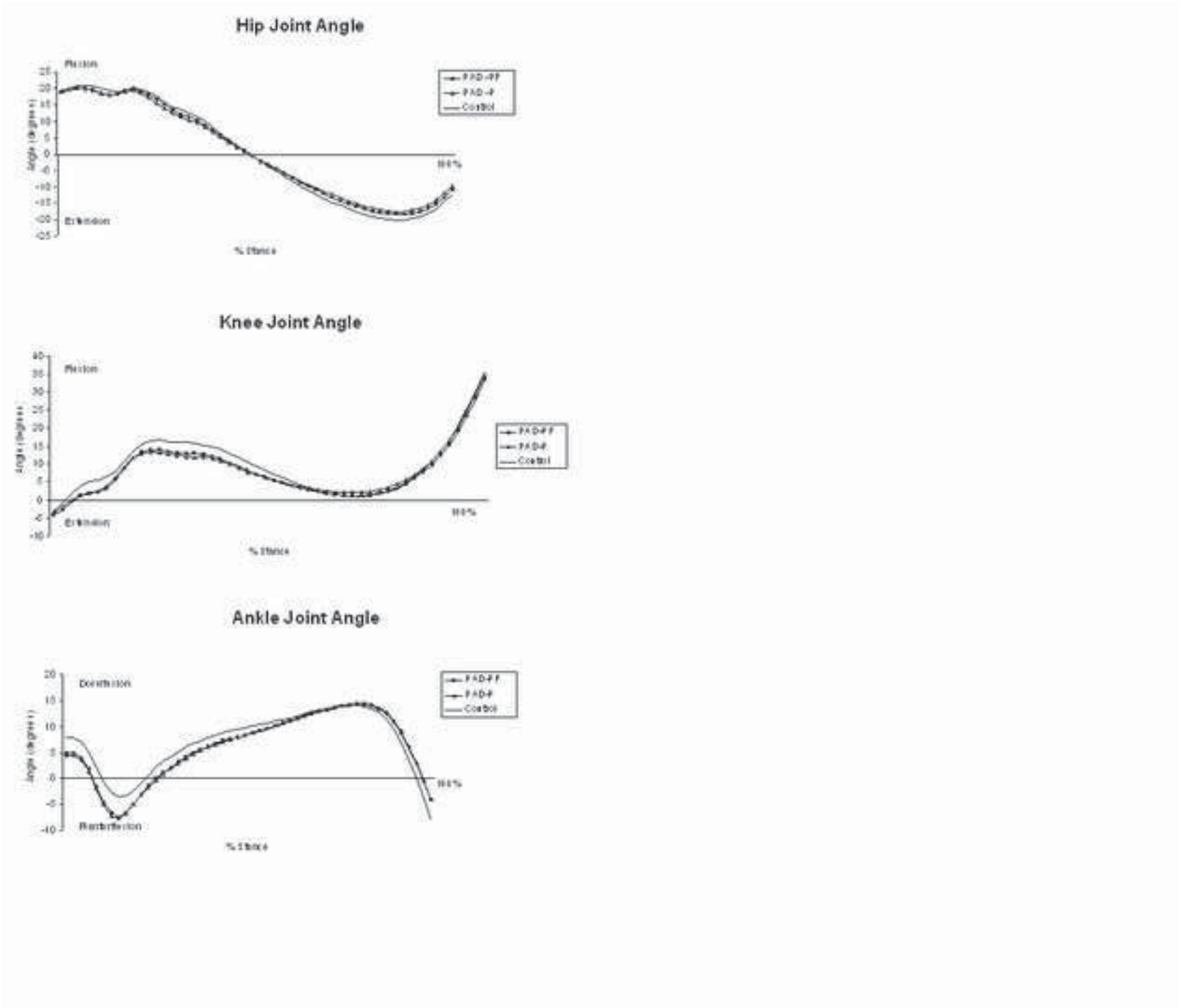

Figure/Table Legend

Figure 1: Anatomic location of markers in lower extremities. The position and trajectories of these markers were captured by our cameras. The analysis and process of this data originates curves corresponding to relative joint angles during stance time of the selected limb.

Figure 2. Average curves for hip, knee and ankle joints representing healthy control patients and PAD-PF and PAD-P conditions.

Table 1. Group means of joint angle parameters in controls and PAD patients both before and after the onset of claudication.

PAD-PF, pain free condition PAD patient; PAD-P, pain condition PAD patient; NS statistically non significant; ROM, range of motion

† Control vs. PAD-PF

‡ Control vs. PAD-P

ʃ PAD-PF vs. PAD-P

Table 2: Group means of time to maximal flexion and extension of the joints in controls and PAD patients both before and after the onset of claudication.

PAD-PF, pain free PAD patient; PAD-P, pain condition PAD patient; NS statistically non significant; ROM, range of motion

† Control vs. PAD-PF

‡ Control vs. PAD-P

ʃ PAD-PF vs. PAD-P