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Denise McGrath
University of Nebraska at Omaha

Timothy N. Judkins
University of Nebraska at Omaha

Iraklis Pipinos
University of Nebraska Medical Center

Jason Johanning
University of Nebraska Medical Center

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Peripheral Arterial Disease Affects the Frequency Response of Ground Reaction Forces During Walking

Denise McGrath, PhD[a], **Timothy N. Judkins, PhD**[b], **Iraklis I. Pipinos, MD**[c,d], **Jason M. Johanning, MD**[c,d], and **Sara A. Myers, PhD**[a]

[a]Nebraska Biomechanics Core Facility, University of Nebraska at Omaha, Omaha, NE, USA

[b]Intelligent Automation, Inc., Rockville, Maryland, USA

[c]Department of Surgery, University of Nebraska Medical Center, Omaha, NE, USA

[d]Department of Surgery, Veterans Affairs Medical Center of Nebraska and Western Iowa

Corresponding Author: Dr. Sara A. Myers, Nebraska Biomechanics Core Facility, University of Nebraska, Omaha, HPER 207, 6001 Dodge Street, Omaha, NE 68182, USA. samyers@unomaha.edu.

Abstract

Background—Walking is problematic for patients with Peripheral Arterial Disease. The purpose of this study was to investigate the frequency domain of the ground reaction forces during walking to further elucidate the ambulatory impairment of these patients.

Methods—Nineteen bilateral peripheral arterial disease patients and nineteen controls were included in this study. Subjects were matched for age and gait speed. Participants walked over a force plate sampling at 600Hz. PAD patients were tested before (pain-free condition) after the onset of claudication symptoms (pain). We calculated median frequency, frequency bandwidth, and frequency containing 99.5% of the signal for the vertical and anterior-posterior ground reaction forces.

Findings—Our results showed reduced median frequency in the vertical and anterior-posterior components of the ground reaction forces between the control group and both peripheral arterial disease conditions. We found reduced frequency bandwidth in the anterior-posterior direction between controls and the peripheral arterial disease pain-free condition. There were no differences in median frequency or bandwidth between peripheral arterial disease pain-free and pain conditions, but an increase in the frequency content for 99.5% of the signal was observed in the pain condition.

Interpretation—Reduced frequency phenomena during gait in peripheral arterial disease patients compared to velocity-matched controls suggests more sluggish activity within the neuromotor system. Increased frequency phenomena due to pain in these patients suggests a more erratic application of propulsive forces when walking. Frequency domain analysis thus offers new insights into the gait impairments associated with this patient population.

Keywords

Gait; intermittent claudication; occlusion; power spectrum

Introduction

Peripheral Arterial Disease (PAD) is the result of atherosclerotic occlusion of the leg arteries affecting 8 to 12 million people in the United States (Menard et al., 2004). Walking is problematic for patients with PAD for two specific reasons. First, there is marked mitochondrial dysfunction and neuromotor dysfunction associated with the disease that affects initial ambulation i.e. during the first steps that a person takes in the pain free state. Secondly, this baseline neuromotor dysfunction is further exacerbated by increased metabolic demand of active leg muscles that are not satisfied due to restricted blood flow to the lower extremities. The restricted blood flow results in reduced muscular

oxygenation during physical activity causing progressive ischemia and pain (McCully, Leiper, Sanders, & Griffen, 1999). This cramping pain in the calves, thighs and/or buttocks is called claudication and occurs with variable onset time during ambulation. The reduced mobility and poor gait performance that results from PAD is a great concern in the management of these patients. Analysis of the walking patterns in PAD patients has accordingly received much attention within the research community.

PAD patients have been shown to walk differently from healthy control subjects in terms of shorter walking distances (McDermott et al., 2001), slower walking speed (Watson et al., 2011), shortened step length and reduced cadence (Gardner, Forrester, & Smith, 2001). Recently, more detailed biomechanical evaluations have included analysis of lower-limb joints and muscles (Celis et al., 2009; Chen et al., 2008; Koutakis, Johanning et al., 2010; Myers, Pipinos, Johanning, & Stergiou, 2011; Scott-Pandorf et al., 2007). These studies have shown altered joint kinematics and joint powers in patients with PAD. These biomechanical parameters are typically analyzed through the identification of local discrete points and their respective times of occurrence. This approach is referred to as time domain analysis, where the data are examined as a function of time. However, time domain analysis examines discrete points rather than the global make-up of the data. An alternative approach that takes the entire structure of the data into account is the frequency domain analysis.

In the frequency domain, data are represented as a function of frequencies rather than time, and are characterized by the patterns of oscillations present in the data (Giakas, 2004). Frequency domain analysis of biomechanical measures such as ground reaction forces (GRF) has been used to assess the frequency content of healthy and pathological gait signals (Crowe, Schiereck, de Boer, & Keessen, 1995; Giakas & Baltzopoulos, 1997; Giakas, Baltzopoulos, Dangerfield, Dorgan, & Dalmira, 1996; Stergiou, Giakas, Byrne, & Pomeroy, 2002; White, Agouris, Selbie, & Kirkpatrick, 1999; Wurdeman, Huisinga, Filipi, & Stergiou, 2011). The development of GRF during the stance phase of walking reflects the neuro-mechanical function of the lower limb joints and muscles. An examination of the frequency content of the GRF will reveal high or low frequency phenomena present in these structures. Wurderman et al. (2011), in their study on multiple sclerosis patients, suggested that frequency domain analysis of GRF could potentially provide earlier insights into the progression of the disease.

Therefore, the purpose of this study was to investigate the frequency domain of the vertical and anterior-posterior GRF of PAD patients during walking to further elucidate the ambulatory impairment of these patients. An important characteristic of this study is that the PAD patients are matched to a control group in terms of age and gait speed. The frequency content of a gait signal is inherently related to the speed of movement. The fact that we have velocity-matched our two groups results in a particularly robust design that enables us to attribute differences in frequency content to the disease alone, and not to disparate speeds of movement. We hypothesized that the PAD group would have lower frequency content than the control group, based on previous studies in other pathological populations (Stergiou et al., 2002; Wurdeman et al., 2011). PAD patients have exhibited altered gait both before and after the onset of claudication (Koutakis, Johanning et al., 2010; Myers et al., 2011). We therefore hypothesized that PAD patients would differ from controls in both the pain-free and pain conditions. Additionally, we hypothesized that the PAD patients would exhibit lower frequency content when in pain than when not in pain.

Methods

Participants

Nineteen bilateral PAD patients and nineteen controls were included in this study (Table 1). These patients were selected from a larger database of PAD patients and control subjects on the basis of matched gait speeds. Patients were matched to controls one to one within ± 10% of each patient's walking velocity. Only right legs from both groups were analyzed. Patients were recruited from the clinics at the Nebraska Western Iowa Veterans Affairs Medical Center and the University of Nebraska

Medical Center. Diagnosis consisted of history and physical examination with confirmation of PAD disease via non-invasive testing and by computed tomography scanning, magnetic resonance imaging, or invasive angiography. Healthy control subjects were recruited from the community and also completed a detailed history and physical examination after enrolling in the study. Patients were screened and evaluated by board certified vascular surgeons and excluded if the presence of ambulation limiting cardiac, pulmonary, neuromuscular or musculoskeletal disease was identified. Written informed consent was obtained from all participants prior to participation in accordance with the Institutional Review Boards of the participating sites.

Experimental Procedure and Data Collection

Participants walked at a self-selected pace over an embedded force plate on a 10m walkway while the GRF was recorded at 600Hz. Each PAD patient was tested first in the pain-free condition (before the onset of claudication symptoms), followed by the pain condition (after the onset of claudication symptoms). For the pain-free condition, a mandatory rest period of at least one minute was implemented between five walking trials to prevent the onset of pain. Once patients had completed all pain-free 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 $0.67 ms^{-1}$ until the patient reported onset of pain. At this time patients immediately dismounted the treadmill and returned to the motion capture area to acquire five walking trials for the pain condition without the mandatory resting period between trials. The controls completed five walking trials with 1-minute rest periods between trials.

GRF is the force applied by the subjects' weight bearing limb during the stance phase of gait. It is a direct application of Newton's third law of motion concerning action-reaction (Winter, 1984). As the subject walks across the plate and pushes the ground with a force, the ground exerts an equal and opposite force called the reaction force. This force is resolved into the vertical, anterior-posterior and medial-lateral components based on the planes of motion. For the purposes of this study, only vertical and anterior-posterior forces were analyzed as our previous work has shown many differences between controls and PAD patients in the vertical and anterior-posterior GRF, while findings in the medial-lateral direction have not been as robust (Scott-Pandorf et al., 2007). We were therefore interested in gaining further insight into these particular components.

Frequency Analysis

We performed a frequency analysis by first converting the anterior-posterior and vertical GRF of each trial to the frequency domain using the fast Fourier transformation implemented in MATLAB (Matlab 6.5, Mathworks, Inc., Concord, MA). The fast Fourier transformation is a method that decomposes a signal into its constituent frequencies (Giakas, 2004). Movement can be thought of as a collection of movements of multiple parts (joints, muscles, bones, nerves) that all operate at different speeds, but collectively the parts move together and therefore represent a "sum". The components that contribute to the movement are usually periodic, that is, they repeat the same action multiple times. The frequency of movement is the number of times it repeats, or oscillates, each second (the faster the movement, the higher the frequency). The fast Fourier transformation calculates the amount of the movement that occurs at each respective frequency. The array of different frequencies that emerge is known as the power spectrum. Figure 1 illustrates a simple example of the fast Fourier transformation and power spectrum. Based on previous studies (Stergiou et al., 2002; Wurdeman et al., 2011) and our pilot work, from the power spectrum that described our data, we obtained the dependent variables of median frequency, frequency bandwidth, and the frequency that contained 99.5% of the signal for the vertical and anterior-posterior GRF of each trial. Median frequency is the point where half of the total power is above and below that frequency. It is calculated as:

$$\int_0^{f_{med}} P(f)df = \int_{f_{med}}^{f_{max}} P(f)df \quad (1)$$

Where f_{med} is the median frequency, $P(f)$ is the power at frequency f, and f_{max} is the maximum frequency of the power spectrum. Frequency bandwidth is the difference between the maximum and minimum frequency when the power is greater than ½ the maximum power. The 99.5% frequency is the frequency at which 99.5% of the power spectrum is contained, as calculated by:

$$\int_0^{f_{99.5}} P(f)df = 0.995 \times \int_0^{f_{max}} P(f)df \quad (2)$$

Statistical Analysis

We performed two independent t-tests comparing the control limb versus the PAD limb in the pain-free condition, and the control limb versus the PAD limb in the pain condition for each dependent variable from the vertical and anterior-posterior GRF. A dependent t-test was also carried out to analyze differences between the PAD pain-free and PAD pain conditions. The level of significance was set at α = 0.05.

Results

In the control versus PAD pain-free condition comparison, significant differences were observed for the median frequency in both the vertical (p=0.037) and anterior-posterior (p=0.031) components of the GRF (Figure 2a). The PAD patients exhibited lower median frequency values. Similarly, in the frequency bandwidth, a significantly lower value was observed in the PAD group compared to controls in the anterior-posterior component of GRF (p=0.042), but not in the vertical component (p=0.592). No differences were found in the 99.5% frequency variable in either the vertical (p=0.199) or the anterior-posterior GRF (p=0.245).

In the control versus PAD pain condition, similar results were observed as in the control versus PAD pain-free condition (Figure 2b). Again, significant differences were observed for the median frequency in both the vertical (p=0.033) and the anterior-posterior GRF (p=0.043), with PAD patients exhibiting lower values. While PAD patients also demonstrated lower frequency bandwidth values in the anterior-posterior GRF, this was not statistically significant (p=0.086). No differences in frequency bandwidth were observed in the vertical GRF (p=0.579). Likewise, no differences were observed in 99.5% frequency in the vertical (p=0.669) or anterior-posterior GRF (p=0.984).

In the PAD pain-free versus PAD pain condition, no differences were observed in the median frequency or the frequency bandwidth variables (Figure 2c). However, a significant difference (p=0.009) was observed between the two conditions for 99.5% frequency in the anterior-posterior GRF, with higher frequencies revealed in the pain condition. No differences were observed in the vertical GRF for this variable (p=0.787).

Discussion

The purpose of this study was to determine if there are differences in the frequency content of the GRF during gait in patients with PAD and an age-matched control group. Importantly, both our groups were also matched for gait speed, which means that differences observed can be attributed to the disease alone, and not to differences in gait velocities. Our hypotheses were partially supported:

PAD patients did exhibit reduced median frequencies in both the vertical and anterior-posterior GRF compared to controls. This held true for both PAD pain-free and pain conditions. This was also the case for frequency bandwidth in the anterior-posterior direction. On the other hand, results from frequency bandwidth in the vertical GRF, and 99.5% frequency did not support our hypothesis. Similarly, comparisons between PAD pain-free and pain conditions for median frequency and bandwidth did not support our hypothesis. While there was a statistically significant difference found between conditions for 99.5% frequency, this was in the opposite direction to what was expected.

Median Frequency

Reduced median frequency in PAD patients compared to controls was observed in both pain-free and pain conditions. Reduced median frequency indicates, on average, more sluggish oscillatory components within the neuromotor system as the body applies force to the ground during walking. These results are consistent with other studies that show differences in gait between PAD patients and healthy controls, regardless of pain status (Celis et al., 2009; Chen et al., 2008; Koutakis, Johanning et al., 2010; Myers et al., 2011). Altered gait that is present before the onset of claudication symptoms suggests that these differences are due to chronic changes in the neuromuscular system associated with PAD. Muscle fiber type shift has been observed in PAD, where a change in fiber type to more type I fibers has been reported (Steinacker et al., 2000). However, the results of investigations into this phenomenon have not been entirely consistent, possibly due to the inherent sampling variability that is associated with needle biopsy techniques in humans (Pipinos et al., 2008). A shift in muscle fiber type in PAD to more type I fibers could be consistent with the lower median frequencies found in this study since type I fibers exhibit slower contractile kinetics than type II fibers. Slower contractile kinetics would manifest as less oscillatory components within the muscle and hence lower overall median frequencies. Further work is required to develop this hypothesis by exploring the possible relationship between fiber type shift and movement frequencies in PAD. If this relationship is confirmed, this type of gait analysis could potentially play an important role in screening for and diagnosing stages of the disease.

Frequency Bandwidth

Differences in the frequency bandwidth of GRF were observed between the control versus PAD pain-free condition and the control versus PAD pain condition in the anterior-posterior direction, although the differences were not statistically significant in the latter. However, no differences were observed in the vertical GRF. This finding suggests that there was a reduced range of movement frequencies available to the PAD patients as they propelled themselves forwards through the stance phase that was not evident in the vertical direction. Frequency analysis of movement determines the range of frequencies associated with all components of the neuromotor system, bones, muscles, nerves, connective tissue, as they interact with each other to produce movement. Reduced bandwidth of movement frequencies indicates constrained oscillatory phenomena in one or more of these structures as the patient moves in the anterior-posterior direction. Wurdeman et al. (2011) found differences in the frequency content of vertical GRF in patients with multiple sclerosis, but not in the anterior-posterior component. The authors suggested that changes in the frequency component organization may be affected differently, depending on the disease or impairment. They associated changes in the vertical GRF frequency content with upright support forces and the fact that a considerable portion of multiple sclerosis patients end up with a cane or a wheelchair to maintain mobility. In PAD, we know that patients experience difficulty with forward propulsion. Previous research has identified reduced ankle plantarflexion power generation in the anterior-posterior direction during late stance in both PAD pain-free and pain conditions compared to controls (Koutakis, Pipinos et al., 2010). Thus, the limited range of oscillatory phenomena within the neuromotor system in this plane of motion may relate to the functional challenges associated with forward propulsion. While this analysis does not identify the

movement frequencies associated with each separate anatomical structure (bones, muscles, nerves, connective tissue), it is possible that the reduced frequency bandwidth is related to the myopathy associated with PAD.

99.5% Power of the Signal

The power spectrum of the GRF relates to the amplitude of each frequency that is represented in the signal. The frequency content required to reconstruct 99.5% of the signal's power quantifies the oscillations within the GRF. This variable was not different between PAD patients and controls. However, the differences observed between the PAD pain-free condition and the PAD pain condition in the anterior-posterior direction is an interesting finding. Previous research has used the frequency content of GRF as a measure of tremor and instability of the movement pattern (Giakas & Baltzopoulos, 1997; Giakas et al., 1996); the higher the frequency content of the data, the higher the tremor and the instability. This framework suggests that our results may have identified gait instability problems in PAD patients following the onset of claudication. Gardner and Montgomery (2001) have shown that patients with intermittent claudication have an 86% increase in ambulatory stumbling and unsteadiness compared to controls, along with a 73% higher history of falling. It is not clear from our study if the higher oscillatory characteristics revealed in the pain condition are a result of a coping strategy, or a maladaptive strategy that may increase the risk of falling in these patients. It may be a combination of both, where the participant attempts to redistribute the propulsive forces throughout the different structures or muscle fibers of the lower limb in response to the pain (resulting in higher oscillations), but in doing so, produces a more erratic and unstable movement. Future work should investigate the relationship between this phenomenon and falls history in PAD patients. This could lead to more informed falls prevention strategies for this patient population.

Clinical Significance

Frequency analysis of GRF during walking revealed differences between PAD patients and velocity-matched controls. Interestingly, these differences were observed in both pain-free and pain conditions, indicating that this type of analysis may be useful in quantifying the longer term changes that are associated with the advancement of PAD. Additionally, this analysis was able to detect higher oscillatory movement patterns in patients when walking with pain, compared to a pain-free condition. These measures could therefore potentially be used to evaluate the long-term and short-terms effects of surgical or exercise interventions and pharmacological treatments for PAD patients. Implementation of such analysis is feasible in a clinical setting as subjects would simply be required to walk over a force platform to obtain the data, with no devices needing to be attached to the patients. Future work should explore the relationship between the lower frequency phenomenon observed in the PAD patients in both the pain and pain-free conditions, and muscle fiber type composition in terms of disease progression. The relationship between the higher movement frequencies in the pain versus pain-free condition and falls history or falls risk should also be investigated. We conclude that this type of biomechanical analysis has promising clinical application in providing new insights into the gait impairments associated with PAD.

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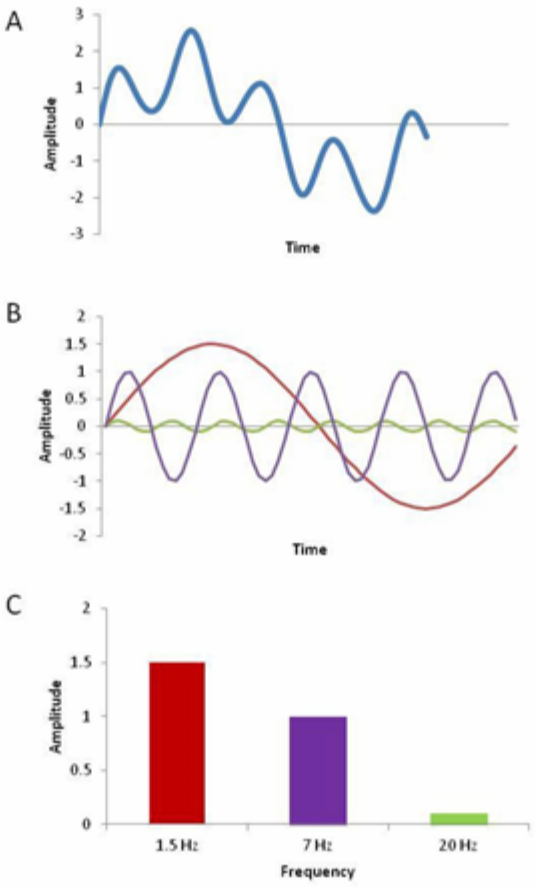

Figure 1.
A simple example of the fast Fourier transform. Graphs A and B depict signals in the time domain and graph C depicts the signals in the frequency domain. The graph in A represents a signal e.g. a movement pattern that we want to analyze. It is comprised of a number of different signals, or sine waves. The fast Fourier transform breaks down a signal into many more simplistic signals, so in this example we end up with three separate movement signals, or sine waves, represented in B. These three movement signals contribute to the global movement pattern that is represented in A. The power spectrum graph in C is a representation of the composite signal A in the frequency domain. There is a large amount of low frequency present (1.5 Hz) in the signal, which comes from the red-lined signal and just a small amount of high frequency (12 Hz) contribution to the signal, which primarily comes from the green-lined signal. Real biological signals like walking are made up of many such signals and are much more complex than the schematic presented here.

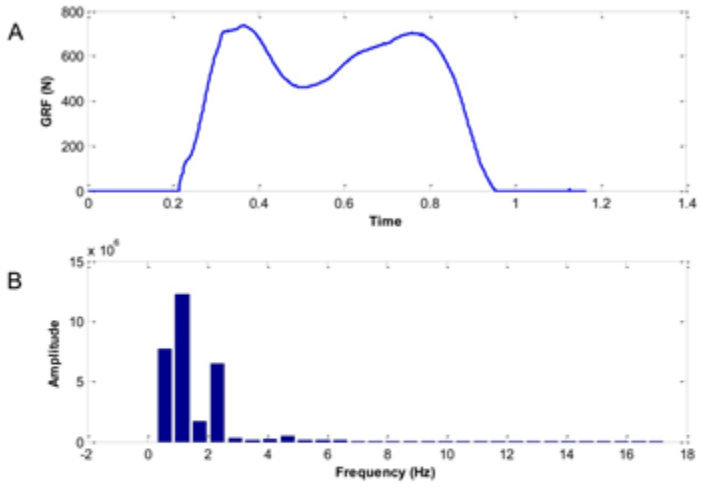

Figure 2.
An example of fast Fourier transform with one representative subject. Graph A depicts a vertical ground reaction force (GRF) of the subject over time. Graph B shows the power spectrum graph of the signal in graph A. In this signal, most of the frequency contents lies between 0 and 4 Hz, however there are some contributions of frequency up to about 18 Hz.

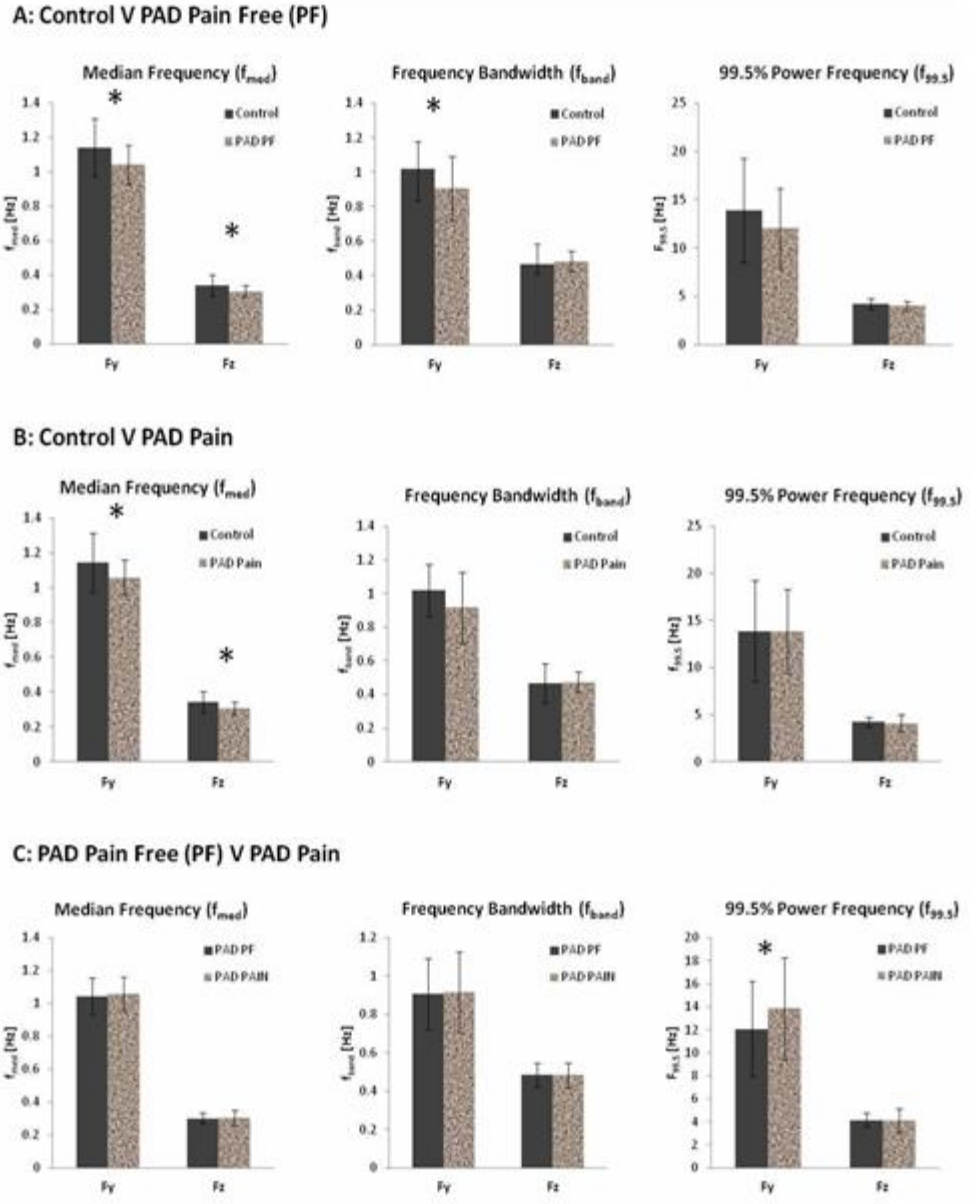

Figure 3.
Median frequency, frequency bandwidth, and 99.5% power frequency for anterior/poster (F_y) and vertical (F_z) GRF across conditions: 2A: Control versus PAD pain-free conditions, 2B: Control versus PAD pain condition, 2C: PAD pain-free versus PAD pain condition. Error bars represent standard deviations of the data series. Statistical significance is denoted by *. $p<0.05$

Table 1

Description of Cohort (M=male, F=female; R=right leg, L= left leg). The Ankle Brachial Index is the ratio of systolic blood pressures taken at the brachial artery in the arm and at the dorsal pedis and anterior tibialis artery at the ankle level. Values less than 0.90 are indicative of having PAD. p-values result from independent t-tests.

	PAD Mean(SD)	Control Mean(SD)	p-value
Gender	15M; 4F	13M; 6F	------
Age (yrs)	60.5 (7.8)	62 (11.7)	0.63
Height (cms)	172.5 (9.2)	170.6 (8.6)	0.49
Weight (kgs)	81.1 (19.5)	81.5 (21.4)	0.94
Gait Speed (ms^{-1})	1.18 (0.14)	1.18(0.15)	0.92
Ankle Brachial	R:0.63 (0.24)	-------	
Index	L:0.59 (0.17)		