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The influence of peripheral arterial disease on lower limb surface myoelectric signals in patients living with type II diabetes mellitus

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ABSTRACT

Background: The aim of this study was to evaluate whether there are any significant differences in muscle activity between individuals living with type II diabetes mellitus (T2DM) and individuals living with T2DM and peripheral arterial disease (PAD), during gait at a self-selected speed. The influence of different stages of PAD on muscle activity during gait was also assessed with the use of surface electromyography (EMG).
Research question: Does PAD affect lower limb muscle activity during gait in the presence of T2DM?
Methods: This quantitative study involves a prospective, comparative, non-experimental subject design. Ninety participants were divided into three groups namely Group A (thirty participants living with T2DM), Group B(i) (thirty participants living with T2DM and mild PAD) and Group B(ii) (thirty participants living with T2DM and severe PAD). Surface electrode sensors were placed according to SENIAM guidelines, on six main lower limb muscles on both limbs. Muscle activity was recorded using a wireless system, where participants were instructed to walk at a self-selected speed on a 10-m walkway. Average Burst RMS was performed and the amplitude (mV) and the duration of muscle activation (s) was analysed.
Results: There was a significant increase in muscle amplitude and duration of activation in the presence of lower limb ischaemia during gait. The largest significant difference ($p = \ < 0.05$) in EMG amplitude and duration of activation when looking at the twelve muscles in general was found between participants living with T2DM and participants living with T2DM and severe PAD.
Significance: The increase in muscle activity indicates that there are musculoskeletal and biomechanical changes in the lower limb musculature with increasing severity of PAD. Higher muscle exertion demands are required during gait which may result in earlier fatigue. EMG tests would be beneficial for detecting muscle dysfunction objectively and non-invasively in T2DM and PAD.

1. Background

Peripheral arterial disease (PAD), also known as peripheral vascular disease or peripheral obliterative artheriopathy, is defined as a partial or complete obstruction of arteries due to atherosclerotic occlusion of the lower extremities [1]. It has been estimated that, globally, there are more than 202 million individuals living with PAD, with 70% of affected people living in countries having a low to moderate financial status [1].

PAD presents a high health, social and human impact [2]. As a result, early identification and prevention of disease is of great significance to reduce the severity of PAD and the risk of amputation. Preventative measures through diabetic, vascular, neurological and musculoskeletal screening are more cost effective than the need for surgical interventions and rehabilitation for advanced PAD [2,3]. Furthermore, preservation of an individual's independence through improving mobility and prevention of pain and risk of ulceration, could significantly improve one's quality of life and provide a better prognosis [4].

Examination and monitoring of individuals living with PAD is more focused on the vascular aspect rather than the effect of PAD on the biomechanical and neurological status of the individual. The role of the treating clinician should be to determine the presence / absence and severity of PAD in the lower limbs, whilst also linking any neurological or musculoskeletal problems to the reduction in blood supply [5].

Literature shows that lower limb ischaemia may result in abnormal gait patterns, thus better evaluation of the effect on muscle activity would enhance our understanding in gait impairment and may lead to

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novel, gait-specific management for PAD [6–8].

The firing rate of muscle fibres during a contraction is usually in the range of 50 to 150 Hz [9,10]. However, as the exertion demand increases, the firing rate shifts to higher frequencies, resulting in higher EMG readings. Moreover, this is also because the motor unit recruitment strategy moves from an asynchronous to a synchronous pattern [11]. Muscle fatigue is associated with inadequate blood perfusion to muscle fibres, depletion of energy sources and a build-up of metabolites. The build-up of excess hydrogen ions slows down the waveform of an action potential in a muscle contraction, resulting in two electrophysiological events; the synchronisation of the motor unit pools resulting in increased amplitude, and the increase in the duration of activation of an EMG signal [12].

Studies investigating the effect of muscle activity in the presence of lower limb ischaemia confirm this tendency when compared to "healthy" participants. Moreover, an increase in EMG amplitude was found even when compared to participants living with T2DM [13–18]. This may be due to the effect of glycosylation where changes in collagen fibres may cause joint stiffness and a resultant decrease in elasticity and flexibility of tissues causing further muscle exertion during movement and earlier fatigue [15,19,20]. However, studies have recruited and classified participants through ankle brachial pressure index (ABPI) testing only, whilst a toe brachial pressure index (TBPI) test is proven to be a more accurate and reliable alternative to diagnose the presence and severity of PAD [21,22].

Further research including larger samples is required to produce more reliable data. To date, literature has also focused primarily on the anterior tibialis and medial gastrocnemius muscles. Thus this study aimed to investigate the influence of PAD on the main lower limb muscles during gait, focusing also on the effect of increasing severity of lower limb ischaemia on these muscles.

2. Method

Ethical approval for this quantitative, prospective, comparative, non-experimental study was obtained from the University Research Ethics Committee and all participants were treated according to the Declaration of Helsinki [23].

Unfortunately, to date there are no local statistics on the prevalence of peripheral arterial disease in Malta, thus the sample size could not be estimated. However, the sampling frequency used during EMG data acquisition was that of 2000 Hz and thus a large amount of data was produced per participant. Moreover, compared to other similar studies [13–18,21], a considerably large sample size of 90 participants was used and both limbs of every participant were assessed, resulting in a total of 180 limbs.

Ninety participants who met the inclusion/exclusion criteria were recruited via purposive sampling and divided into two main groups. Group A comprised thirty individuals living with T2DM and Group B comprised sixty individuals living with T2DM and PAD. Group B was further subdivided into mild PAD (Group Bi) consisting of thirty-two participants and severe PAD (Group Bii) consisting of twenty-eight participants. Individuals living with systemic conditions that might alter the findings of the study such as; polyneuropathy, musculoskeletal disorders, history of lower limb revascularisation, uncontrolled hypertension and hyperlipidaemia, osteoarthritis and rheumatoid arthritis were excluded from the study. For the purpose of this study, classification of participants into three groups was done as shown in Table 1.

Data collection was carried out at the Biomechanics Laboratory, Faculty of Health Sciences, University of Malta, over a span of six months. All participants were instructed to wear shorts during data acquisition for ease of accessibility for placement of EMG sensors. In order to minimise artefacts as much as possible and to improve the quality of myoelectric signals being recorded, skin was prepared by shaving hair, followed by abrasion of the skin and application of 70% alcohol in the areas of sensor placement [24].

Table 1
Classification of Participants.
Adapted from Brooks et al. (2001).

Group	Doppler waveforms	TBPI
Group A (Type II DM only)	Triphasic / Biphasic	> 0.7
Group B (i) (DM + Mild PAD)	Monophasic	0.64–0.7
Group B (ii) DM + Severe PAD)	Monophasic continuous	< 0.64

Muscle activity was recorded using a 16-channel Wireless System (Trigno™, Delsys®, Boston USA) with a sampling frequency of 2000 Hz. The surface electrodes used in this study featured a parallel 4-bar formation with a 99.9% silver contact material, a triaxial accelerometer inbuilt in each electrode, with an inter-electrode distance of 10 mm and a bandwidth of 20–450 Hz (specifically to pick up and analyse muscle activity and eliminate most of the unwanted noise) [25]. The electrode sensors were placed according to SENIAM guidelines on each of the six muscles chosen to be examined in this study on both limbs as seen in Table 2 [26]. Each sensor was tested by viewing the real-time EMG display on Vicon© Nexus Motion Capture Software (Vicon, OMG, Oxford, UK) as the participants were asked to contract each particular muscle, also according to SENIAM guidelines, in order to ensure that each sensor was picking up the signal of each muscle with minimal crosstalk. A Resting Trial was performed to measure the baseline noise, where voluntary isometric contractions were instructed to each participant [27].

An acclimatisation period on a 10-m walkway was performed on each participant at a self-selected speed. This was established following the acclimatisation period from three trials where the speed from each trial was averaged. Data was then recorded where the most accurate five trials with the least amount of noise were chosen out of the eight trials recorded. A digital metronome was set according to the speed each participant had been walking in. This is a previously validated method of guiding the speed of each participant during data capture [28,29]. Any trials exceeding ± 5% of the average warm-up speed were excluded and subsequently repeated.

After acquisition of data was completed, the raw data was transferred to Delsys EMGworks® Analysis software version 4.5.3 for processing and analysis of data. Average Burst RMS was calculated to determine the root mean square (RMS) and then to analyse the amplitude (mV) and the (on/off) duration of peak muscle activation (s) of each muscle during the gait cycle. On/off detection of muscle activation was determined by calculating the regression line of a segment (having a window of less than 50 ms) [30].

The mean value (± SD) of the activation peak (mV) and the mean value (± SD) of the duration of the activation peak (s) of the twelve muscles being tested were transferred to PASW® Statistics 18 (Statistical Package for Social Sciences – SPSS) for statistical analysis to test the hypotheses. The Kolmogorov-Smirnov test was performed to check the normality assumption, where a 95% confidence interval was adopted. Since this study involved comparing mean scores between three independent groups having a metric scale, One-Way ANOVA and Post-Hoc tests were performed.

The whole process of data extraction is summarised in a flow diagram, as seen in Fig. 1.

3. Results

Thirty participants were recruited to form Group A, where 60% were male (n = 18), whilst 40% were female (n = 12). The mean age in this group was 66.3 years (SD, 7.5), with a mean T2DM duration of 12.37 years (SD, 5.24). Group B(i) comprised of thirty-two participants, where 81.25% were male (n = 26), whilst 18.75% were female (n = 6). The mean age was 70.25 years (SD, 9.98), with a mean T2DM duration of 14.6 years (SD, 5.24). Finally, Group B(ii) comprised of twenty-eight

Table 2
Sensor Location.
Adapted from Freriks and Hermans (2000).

Muscle to be Tested	Sensor Location
Rectus femoris	50% on the line from the anterior superior iliac spine to the superior part of the patella
Biceps femoris (long head)	50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia
Gastrocnemius (medial head	On the most prominent bulge of the muscle
Tibialis anterior	1/3 on the line between the tip of the fibula and the tip of the medial malleolus
Peroneus longus	25% on the line between the tip of the head of the fibula to the tip of the lateral malleolus
Extensor hallucis longus	On the most prominent bulge of the muscle on the anterolateral aspect of the shank

participants, where 78.57% were male (n = 22), whilst 21.43% were female (n = 6). The mean age was 70.61 years (SD, 7.04), with a mean T2DM duration of 15.91 years (SD, 7.63).

One-way ANOVA showed a significant increase in muscle amplitude and duration of activation in all the twelve muscles examined during gait when compared between the three groups. As TBPI scores decreased, EMG amplitude and duration of activation in lower limb musculature during gait increased.

The mean amplitude for all twelve muscles in Group A ranged from 0.022 mV (SD, 0.01) and 0.064 mV (SD, 0.09), where the largest amplitude was found in the medial gastrocnemius muscle and the lowest amplitude was found in the extensor hallucis longus muscle. The mean duration of activation in the muscles being tested in this study ranged from 0.146 s (SD, 0.05) and 0.347 s (SD, 0.14), where the longest duration of activation was found in the medial gastrocnemius muscle and the shortest duration of activation was found in the extensor hallucis longus muscle.

The mean amplitude for all twelve muscles in Group B(i) ranged from 0.025 mV (SD, 0.01) and 0.076 mV (SD, 0.09), where the largest amplitude was found in the medial gastrocnemius muscle and the lowest amplitude was found in the extensor hallucis longus muscle. The mean duration of activation in the muscles being tested in this study ranged from 0.213 s (SD, 0.07) and 0.475 s (SD, 0.27), where the longest duration of activation was found in the anterior tibialis muscle and the shortest duration of activation was found in the extensor hallucis longus muscle.

The mean amplitude for all twelve muscles in Group B(ii) ranged from 0.034 mV (SD, 0.01) and 0.099 mV (SD, 0.14), where the largest amplitude was found in the rectus femoris muscle and the lowest amplitude was found in the extensor hallucis longus muscle. The mean duration of activation in the muscles being tested in this study ranged from 0.237 s (0.07) and 0.499 s (SD, 0.11), where the longest duration of activation was found in the medial gastrocnemius muscle and the shortest duration of activation was found in the extensor hallucis longus muscle.

Table 3 illustrates Post-Hoc tests of muscle amplitude and duration of activation respectively of the twelve muscles being examined across the three different groups.

4. Discussion

This study reports a non-coincidental trend in increase in muscle activity with decreasing TBPI scores. The largest significant difference in both EMG amplitude and duration of activation was found between participants living with T2DM and participants living with T2DM and severe PAD.

Only one study has previously reported similar differences in muscle activity and compared between the different stages of PAD [18]. However, only muscle activity of medial gastrocnemius and tibialis anterior were tested, unlike this present research which investigated 12 lower limb muscles. Moreover, this study was conducted 20 years ago and advancements in technology have been made to produce more precise and detailed EMG data.

Results of the present research are congruent with those of Gerdle et al. who report that the pathophysiology of muscle weakness in the presence of hyperglycaemia and PAD may bring about biomechanical gait alterations. During movement, muscle fibres contract at a firing rate ranging from 8 to 50 Hz. However, due to the lack of blood being supplied to the muscles and the effect of glycosylation, there is more muscle exertion and the fibres take longer to contract to produce the desired action [12].

The significant increase in EMG muscle amplitude in participants living with PAD indicates that higher exertion demands are required from the lower limb musculature to produce the desired action during gait which may result in earlier fatigue [11]. As observed during biopsies done in several studies, shrinkage in muscle fibres with resultant muscle atrophy may also cause an increase in the firing rate to higher EMG frequencies. Consequently, identifying muscle characteristics, such as reduced bulk and strength, during the clinical management of the diabetic foot is vital for the provision of more effective therapies to improve muscle area and function. This in turn could improve muscle performance during gait, thus possibly reducing the risk of severity of symptoms related to PAD, such as intermittent claudication and rest pain [8,12].

Additionally, glycosylation of collagen may also cause joint stiffness, resulting in decreased elasticity and flexibility of tissues causing further muscle exertion during movement. Apart from causing earlier fatigue, this alteration in lower limb biomechanics decreases the ability for the foot to adapt to inclined or uneven terrains predisposing the

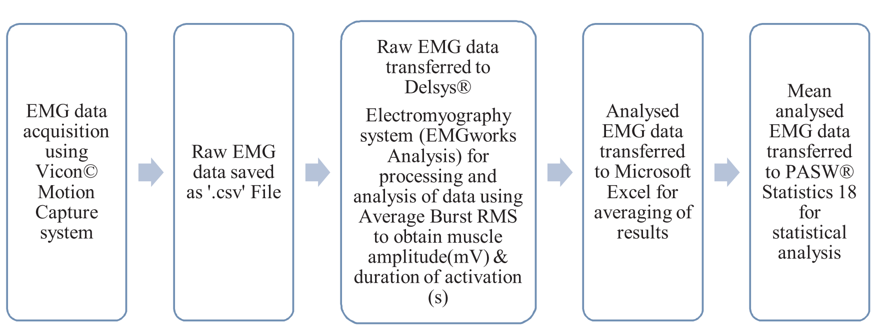

Fig. 1. Flow chart describing the process of data extraction.

Table 3
p-Values of Muscle Activation and Duration of Activation of Right and Left Limbs Between Groups.

p-Values of Muscle Amplitude				p-Values of Muscle Duration of Activation			
	Group A/B(i)	Group A/B(ii)	Group B(i)/B(ii)		Group A/B(i)	Group A/B(ii)	Group B(i)/B(ii)
Rectus Femoris (Right)	0.600	*0.001*	*0.001*	Rectus Femoris (Right)	*0.001*	*0.002*	0.540
Rectus Femoris (Left)	0.995	*0.042*	*0.044*	Rectus Femoris (Left)	*0.013*	*0.001*	0.469
Biceps Femoris (Right)	0.525	0.216	0.805	Biceps Femoris (Right)	*0.005*	*0.001*	0.244
Biceps Femoris (Left)	0.610	*0.031*	0.234	Biceps Femoris (Left)	*0.003*	*0.002*	0.594
Medial Gastrocnemius (Right)	0.195	*0.012*	*0.054*	Medial Gastrocnemius (Right)	*0.048*	*0.003*	0.521
Medial Gastrocnemius (Left)	0.193	*0.001*	*0.003*	Medial Gastrocnemius (Left)	*0.014*	*0.046*	0.914
Anterior Tibialis (Right)	0.898	*0.042*	*0.018*	Anterior Tibialis (Right)	*0.022*	0.204	0.618
Ant erior Tibialis (Left)	0.275	*0.001*	*0.001*	Anterior Tibialis (Left)	*0.001*	*0.002*	0.993
Peroneus Longus (Right)	0.105	*0.001*	0.188	Peroneus Longus (Right)	0.481	0.714	0.938
Peroneus Longus (Left)	0.951	*0.002*	0.007	Peroneus Longus (Left)	0.462	0.151	0.755
Extensor Hallucis Longus (Right)	0.971	*0.001*	*0.001*	Extensor Hallucis Longus (Right)	0.176	*0.014*	0.507
Extensor Hallucis Longus (Left)	0.883	0.113	0.998	Extensor Hallucis Longus (Left)	0.640	*0.025*	0.186

individual to injuries and higher plantar pressures thus increasing the risk of ulceration [4,15,19,20]. This is especially problematic in the elderly population where, with the presence of other comorbidities and age-related lower limb changes (such as arthritis and fat pad atrophy), increases the risk of plantar pressures and tissue stresses and may result in further diabetic complications, such as painful plantar hyperkeratotic lesions and ulceration [2,3].

Resultantly, in the presence of T2DM and PAD, altered muscle activity may be present before the onset of disease-related symptoms, such as intermittent claudication. However, in most cases, advanced biomechanical instrumentation is required to be able to identify any musculoskeletal abnormalities and the extent of the pathology of the ischaemic muscle. Electromyography may serve as another diagnostic and screening tool in the clinical setting to prevent any biomechanical complications related to diabetes and PAD. If any weakness in the lower limb musculature is identified, appropriate physical therapeutic management could decrease muscle exertion demands and the risk of earlier fatigue during gait and resultantly improve gait patterns and pressure distribution of the foot. This could translate in a decrease in the risk of lower limb ulceration and lower amputation rates [7,8].

4.1. Limitations of the study

In order to classify participants into their respective group, TBPI testing was favoured over ABPI testing to limit the possibility of producing artefactually elevated ABPI results due to the presence of non-compressible arteries. However, in the presence of long-standing diabetes, in advanced age, or in end-stage renal disease, there might still be a slight chance for calcification in the lower limb digits to be present [22,23]. Resultantly, to maintain internal validity, participants with kidney disease or distal neuropathy were excluded from this study, whilst those participants with suspected falsely elevated TBPI scores (due to an abnormal pedal waveform and a TBPI score of more than 0.7) were also excluded from this study.

Noise in the signals during EMG data acquisition might still have been misinterpreted as muscle activity during gait. The Trigno™ Wireless System by Delsys® used in this study has a bandwidth of 20–450 Hz, which is adequate to pick up and analyse muscle activity and eliminate most of the unwanted noise [25]. Furthermore, care was taken to prepare the skin and precisely place the EMG sensors according to SENIAM guidelines and a Resting Trial was performed to measure the baseline noise and eliminate it during data processing. Finally, larger surface muscles were chosen, whilst synergists were avoided to prevent the possibility of crosstalk and increase internal validity of data [27].

Previous literature shows that, in the presence of peripheral arterial disease, reduced lower limb joint range of motion, especially at the ankle joint, is present during gait. Moreover, slower gait velocity and reduced stride length was also noted [6,14]. Recommendations for further research include conducting a comprehensive randomised controlled study, with a sample size representative of the whole population living with PAD, analysing the effect of lower limb ischaemia on joint kinetics and kinematics during gait in relation to muscle activation patterns.

5. Conclusion

A key finding in this study is the high significant increase in muscle amplitude and duration of activation found between participants living with T2DM and participants living with T2DM and severe PAD. This demonstrates that electromyographic tests in the clinical setting could provide valuable information with regards to the detection of muscle dysfunction associated with PAD during diagnosis and monitoring of patients living with T2DM and lower limb ischaemia. Surface EMG is a non-invasive method for providing objective information on muscle performance and fatigue in individuals living with T2DM which would aid in identifying any musculoskeletal anomalies at an early stage and possibly prevent lower limb complications associated with the disease.

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Declaration of Competing Interest

None.

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