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Motor strategy patterns study of diabetic neuropathic individuals while walking. A wavelet approach

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ABSTRACT

The aim of this study was to investigate muscle's energy patterns and spectral properties of diabetic neuropathic individuals during gait cycle using wavelet approach. Twenty-one diabetic patients diagnosed with peripheral neuropathy, and 21 non-diabetic individuals were assessed during the whole gait cycle. Activation patterns of vastus lateralis, medial gastrocnemius and tibialis anterior were studied by means of bipolar surface EMG. The signal's energy and frequency were compared between groups using *t*-test. The energy was compared in each frequency band (7–542 Hz) using ANOVAs for repeated measures for each group and each muscle. The diabetic individuals displayed lower energies in lower frequency bands for all muscles and higher energies in higher frequency bands for the extensors' muscles. They also showed lower total energy of gastrocnemius and a higher total energy of vastus, considering the whole gait cycle. The overall results suggest a change in the neuromuscular strategy of the main extensor muscles of the lower limb of diabetic patients to compensate the ankle extensor deficit to propel the body forward and accomplish the walking task.

1. Introduction

Peripheral diabetic neuropathy (DN) impairs both the somatosensory and motor control systems, affecting the amount and quality of sensory information that are essential for the complexity of gait generation and control (Varraine et al., 2002). Gross kinematic, kinetic and EMG alterations in gait (Fernando et al., 2013; Abboud et al., 2000; Akashi et al., 2008; Gomes et al., 2011; Kwon et al., 2003; Sacco and Amadio, 2003; Sawacha et al., 2012), and in other locomotor skills (Maluf et al., 2004; Onodera et al., 2011), have been described since 1970s (Fernando et al., 2013). The study of the potential causes and relying kinematic, EMG and kinetic gait pattern alterations may add to a better diagnostic and therapeutic management of patients.

Fibers of one motor unit appear to be randomly dispersed among fibers of other motor units in which type I and type II fibers are distributed throughout transverse sections in a mosaic pattern (Engel, 1970). Change in the mosaic pattern has been attributed to successive denervation–reinnervation process that happens in diseases of neurogenic origin (Jennekens et al., 1971), as diabetic neuropathy. Motor units become enlarged and a reinnervated muscle fiber changes histochemically according to the type of the motor unit which adopts it. Therefore, fiber type grouping or "enclosed" fibers detection can be an important criterion for the diagnosis of neurogenic disorders (Engel, 1970).

The metabolic changes induced by glucose imbalance lead to accumulation of glycation end-products in muscle fibers (Abboud et al., 2000), reduction of nerve conduction velocity (Almeida et al., 2008) and cross-sectional area of lower limb muscles (Wang et al., 2006), and loss of muscle mass and strength (Andersen et al., 1997; Bus et al., 2002; Lesniewski et al., 2003; Ramji et al., 2007), which result in reduction of motor units. Diabetes mellitus is also responsible for an alteration of the intracellular calcium concentration (Nakagawa et al., 1989; Watanabe et al., 2012), leading to early apoptosis. This interferes in muscle fiber composition, since

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type I fibers are more sensitive to this electrolyte than type II fibers (Ruff and Whittlesey, 1991; Widrick et al., 1996a). It is possible that diabetic subjects with DN have greater loss of type I fibers, which commonly generates force for prolonged periods with lower energy and frequency, and, consequently, their force production depend on higher firing rate fibers which are the remaining type II fibers in their skeletal muscles (Bottinelli et al., 1996; Widrick et al., 1996a, 1996b). The term "energy" refers to electrical energy produced by a muscle captured by EMG, and by "frequency", we refer to result of the firing rates of the muscle fibers captured by the EMG electrodes.

These morpho-histological changes associated to the typical neurological deficit of the DN, would result in an inefficient motor unit recruitment (Wakeling et al., 2006) and a movement generation with an inappropriate muscle activation during walking. These motor consequences would be reflected in the outcomes of an EMG evaluation of diabetic patients. There are descriptions of alterations in the activation timing of lower limb muscles' of DN patients during some locomotor tasks (Akashi et al., 2008; Gomes et al., 2011; Onodera et al., 2011; Sacco et al., 2010; Sacco and Amadio, 2003).

The described timing changes in the EMG in DN population are subtle (4–7%), mostly studied in stance, and is still not consistent among authors (Abboud et al., 2000; Akashi et al., 2008; Gomes et al., 2011; Kwon et al., 2003; Sacco et al., 2010; Sacco and Amadio, 2003; Sawacha et al., 2012). Akashi et al. (2008) and Gomes et al. (2011) showed a delayed activation of gastrocnemius lateralis, however Kwon et al. (2003) saw an anticipation of soleus and medial gastrocnemius activation in DN patients, in addition to a prolonged cessation times of soleus, tibialis anterior and vastus medialis. Contradictorily, Abboud et al. (2000) and Sacco and Amadio (2003) saw a delayed activation of tibialis anterior in DN patients.

These inconsistent EMG findings and some contradictions among studies could be attributed to an imprecise diagnosis and classification criteria for DN, leading to an over- or underestimation of the disease status. Authors may have allocated neuropathic patients to groups considered free from this disease, and vice-versa. Another possible explanation might be related to the EMG procedures adopted, such as electrode placement, noise filtering, and selectivity of the investigated muscle's area, particularly when assessing smaller muscles with higher possibility of EMG cross talk (Blanc and Dimanico, 2010).

All of these EMG studies in diabetics used a conventional analysis in time domain of rectified EMG data, extracting discrete parameters, which are rather limited. Root mean squares and variables of EMG signal ensemble averages may provide information about timing and intensity, but they do not provide appropriate information simultaneously in time, frequency and magnitude domains (von Tscharner, 2000).

In the application of the uncertainty principle of Heisenberg, the exact moment and frequency of the EMG signal's energy cannot be determined with precision simultaneously. The wavelet approach bypasses this situation using waves and windows with variable sizes, and allows a better analysis of high frequencies that occur in a narrow time window or low frequencies in wider periods of time. The familiar Fourier transform decomposes a waveform into a sine wave and a family of harmonics. The unit of decomposition of the wavelet transform is a specific transient signal from a set of different functions of finite duration called wavelets (mother wavelets). Unlike Fourier transform, which may not be applied to transient signals and may lose information on the specific frequency contents of each component, the wavelet transform is an adequate tool for extraction of this type of information. It would be possible to study the muscle activation pattern of DN individuals with a new time/frequency analysis beyond the classic discrete analysis of EMG.

During the last two decades, many extraction techniques of EMG signals have been proposed in several domains when investigating diabetic individuals, notably the time domain (Abboud et al., 2000; Akashi et al., 2008; Gomes et al., 2011; Kwon et al., 2003; Sacco et al., 2010; Sacco and Amadio, 2003; Sawacha et al., 2012), the frequency domain (Allen et al., 2014) and the time–frequency or time-scale domain (von Tscharner, 2000). Among techniques of EMG analysis, discrete wavelet transform is a time-scale approach that has been used successfully in many applications and has improved the analysis of non-stationary signals, including EMG signal. To achieve optimal performance in the wavelet analysis, a suitable wavelet function must be employed, and this choice is usually a very delicate and important problem (Englehart et al., 2001; Oskoei and Hu, 2007; Pauk, 2008; Phinyomark et al., 2012). Although promising, this technique has not been used in the diabetic population yet.

Based on the muscles' structure, function and innervation changes in diabetic individuals, our hypothesis is that the muscles of DN individuals would produce lower energy of the EMG signal mostly at lower frequencies, since there will be a lower energy production of type I fibers which commonly generates lower energy and lower firing rates. The purpose of this study was to investigate muscle's energy patterns and spectral properties of DN individuals during the whole gait cycle, using a novel approach in this population: wavelet analysis technique.

2. Methods

2.1. Subjects

We evaluated 42 volunteers divided equally into a control group (CG), composed by non-diabetic individuals (mean(SD): 53.5(7.6) years; 71.0(14.0) kg; 163(8) cm, 26.6(3.9) kg/m^2; 41% of men), and a diabetic group (DG), composed by subjects with clinical diagnosis of DN (mean(SD): 56.4(7.7) years; 80.8(15.4) kg; 167 (11) cm, 32.0(14.7) kg/m^2; 40% of men, 15(6.2) years of diabetes diagnosis), a median of 6 out of 13 in the Michigan Neuropathy Screening Instrument (MNSI) questionnaire score and a median of 4.5 out of 10 in the foot physical assessment score. Groups were not statistically different in age ($p=0.750$, two-sided *t*-test), sex ($p=1.000$, chi square test), height ($p=0.267$, *t*-test), body mass ($p=0.075$, *t*-test) and body mass index ($p=0.112$, *t*-test).

The DG group was clinically diagnosed and the inclusion criteria consisted of the following: 5 years of diagnosed type 2 diabetes; a score of 3 (out of 13) on the MNSI-questionnaire; and a score of 4 (out of 10) on the Physical assessment of foot. The MNSI-questionnaire is a validated instrument for screening the symptoms related to diabetic neuropathy, and the physical assessment is a tool to evaluate the individuals' feet looking for evidence of excessively dry skin, callus formation, fissures, frank ulceration or deformities such as flat feet, hammer toes, overlapping toes, halux valgus, joint subluxation, prominent metatarsal heads. It includes touch tests (10 g Semmens–Weinstein monofilament) on the foot areas, vibration perception threshold tests on the hallux and ankle reflexes. Both instruments (questionnaire and physical assessment) were applied by a physical therapist experienced in assessing neuropathy and diabetic feet.

The exclusion criteria for both groups were: age over 65 years; partial or total amputation of feet; presence of Charcot arthropathy (or any other major orthopedic foot alteration confirmed by radiography); peripheral or central neurological disease not caused by diabetes; retinopathy or nephropathy; plantar ulcers at the time of the evaluation, and an inability to walk without the use of an assistive device. All procedures were approved by the local Ethics Committee and the participants gave their written informed consent.

2.2. Procedures

The EMG activity of tibialis anterior (TA), vastus lateralis (VL) and gastrocnemius medialis (GM) were measured by an EMG system (800C model, 8 channels, EMG System do Brasil, Brazil) during level walking. These muscles were chosen to be studied due to their essential role in gait progression (VL, GM), as well as knee and ankle impact attenuation (VL, TA). Disposable Ag/AgCl circular electrodes (⌀ = 10 mm) were placed with an inter-electrode distance of 20 mm center to center, over each muscle of the selected limb for each participant after shaving and cleaning skin with rubbing alcohol. VL electrode placement followed the recommendations of SENIAM (Hermens et al., 2000), and for TA and GM, the electrode