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Recurrence quantification analysis of sustained sub-maximal grip contractions in patients with various metabolic muscle disorders

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ABSTRACT

Recurrence quantification analysis (RQA) was used to analyse force signals during sustained sub-maximal grip contraction (SSGC) of three types of patients suffering from a metabolic muscle disorder (glycogen storage disease type III (GSD III), glycogen storage disease type V (GSD V) and mitochondrial myopathies (MITO)) compared to control subjects. Recurrence plots (RP) of patients showed clear non-uniformity, in comparison to control subjects who displayed quasi-periodic patterns. Quantitative analysis of the RP showed significant differences between patients with metabolic disorders and the control group for four RQA parameters. The results showed that the SSGC signals of patients had decreased L_{max}, which indicated more chaotic patterns. In addition the deterministic component of the signals was less complex for patients than for controls. The differences of SSGC signal observed using RP and RQA were possibly related to the underlying changes in metabolism of muscle fibres due to the disease. Results of this study illustrate that the RQA technique is well suited to analyse sustained grip-force signals.

1. Introduction

Grip strength assessment has proven to be a useful tool in the evaluation of neuromuscular disorders [1,2], geriatric [3] frailty [4] and adolescents' growth [5]. A variety of different test protocols, such as maximal grip strength (MGS) and sustained maximal grip contraction (SSGC) tests, have been developed due to the fact that motor strategy [6,7], muscle fatigue [8] and force output [9] depend on the measurement conditions and task demands. The test of sustained sub-maximal grip contraction (SSGC) is another grip strength measurement that requires the subject to maintain a stable grip strength exerted at a certain percentage of MGS, with protocols lasting from a few seconds to a few minutes. The level of effort used in previous studies had varied widely, ranging between 20% and 80% MGS [8,10–15]. The main aims of the SSGC are to evaluate fatigue resistance [8,15], tremor [16], as well as other physiological indices such as heart rate, cardiac output, oxygen uptake, and arterial blood pressure [17,18]. Additionally, the unsteadiness in muscular contraction has been shown to be linked to an increased risk of fall, particularly if this unsteadiness is unilateral [19].

Metabolic muscle disorders, such as glycogen storage disease type III (GSD III), glycogen storage disease type V (GSD V) or mitochondrial myopathies (MITO), may directly affect muscle contraction since they are characterised by a defect in the muscle metabolism [20–23]. Glycogen storage disease type III is an autonomic recessive metabolic disorder that is characterised by a deficiency in glycogen debranching enzyme [24]. Approximately 85% of patients with GSD III have both liver and skeletal muscles affected, with clinical examinations revealing hepatomegaly in children. The progression of the disease results in conditions such as hypotonia and cardiomyopathy [25]. Abnormality in skeletal muscle mechanics of GSD III patients can be observed using grip force testing in conjunction with electromyography [20]. Glycogen storage disease type V (GSD V), more commonly known as McArdle's disease, is another muscle disease associated with a metabolic disorder caused by a deficiency of myophosphorylase [26]. Symptoms include exercise intolerance, muscle pain, fatigability and muscle cramping [23]. A forearm exercise such as squeezing a hand dynamometer for a specific period of time was traditionally performed as a laboratory test [22,23]. Mitochondrial myopathies (MITO) are caused by a defect in either a mitochondrial gene or a gene in the cell nucleus. MITO has a complex array of symptoms. Some symptoms can be hardly noticeable, while others are life-threatening. Symptoms of MITO include muscle weakness, muscle cramping, fatigue, lack of endurance and poor balance. A diagnosis of MITO can be performed using a forearm exercise [22] as well as an electromyography examination.

The main hypothesis of the present study is that the effects of metabolic disorders could be detected and quantified during a SSGC

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test associated with advanced signal processing methods. Grip-force signals (force vs. time) are by nature highly complex, exhibiting nonlinear and non-stationary characteristics [27]. Such a complexity is due to the interaction of multiple feedback loops to regulate each physiological process, as well as the involvement of a large number of different structural units [28]. This complexity renders most of the usual signal description methods irrelevant, which is probably the reason that most of the previous studies on SSGC failed to detect the underlying complexity of strength generation [8,16].

To overcome this limitation, empirical investigations and theoretical modelling studies have been conducted, suggesting that nonlinear dynamical systems theory was a possible candidate for a unified mathematical framework modelling the dynamics of physiologic signals [29]. Recurrence quantification analysis (RQA) is one such nonlinear approach. The first step of applying the RQA is to reconstruct the phase space from the observed time series [30,31]. Based on the local recurrence or neighbourhood structure of the points in the reconstructed phase space, a recurrence plot (RP) can be constructed. Although it is possible to observe recurrence directly in the RP, such recurrence can be difficult to quantitatively evaluate. To this end, the RQA method has been proposed in order to quantify a number of characteristics that can be visually observed within the RP patterns. The RQA method has been shown to be relevant in many applications related to biomedical signal processing such as EEG, EMG, and ECG [32–35]. RQA has been also used for both short-duration and noisy signals [36,37], making it particularly suitable for grip-force signal analysis.

The aim of the present study was to apply RQA to SSGC signals obtained from patients with neuromuscular disorders (GSD III, GSD V, MITO) and control subjects, in order to identify the possible variability in force control strategies due to different metabolic defects of the muscle.

2. Materials and methods

2.1. Subjects

All subjects were selected from a database of over 1000 subjects that underwent a grip test, within the frame of routine examination for the detection of a possible metabolic defect [38]. Sixty-two subjects were extracted from this database. Their characteristics are given in Table 1. All subjects were assessed as part of their medical consultation, which included the grip-force test. In the three patient groups, the diagnosis was established by genetics, a biopsy for histochemistry, or an assessment of the respiratory chain. The control group was composed of patients without any neuromuscular disorder, based on the same diagnostic process. No significant gender effects were found in force curve patterns and parameters, therefore men and women were pooled together for analyses.

2.2. Experimental protocol

Subjects were seated on a chair facing a computer screen, with their shoulders adducted and their testing arm close to their body, with a 110–130° elbow extension and a small wrist extension (Fig. 1). Each subject was tested only for their dominant hand. MGS values were evaluated as the maximal value of three maximal voluntary contractions lasting about three seconds, with 1 min rest between trials. After the MGS trials, subjects were given a 5-min rest before performing a SSGC. For the SSGC, subjects were required to maintain, as stable as possible, an isometric contraction at 70% of their MGS for 30 s within an acceptable region (±3% MGS) displayed on the screen. In order to eliminate psychological effects and adaptations of the grip level linked to the start and the end of the test, the first 5 s and the last 5 s of the SMVC were removed, with the remaining 20 s used for all subsequent analyses. Subjects were given verbal encouragement for all efforts.

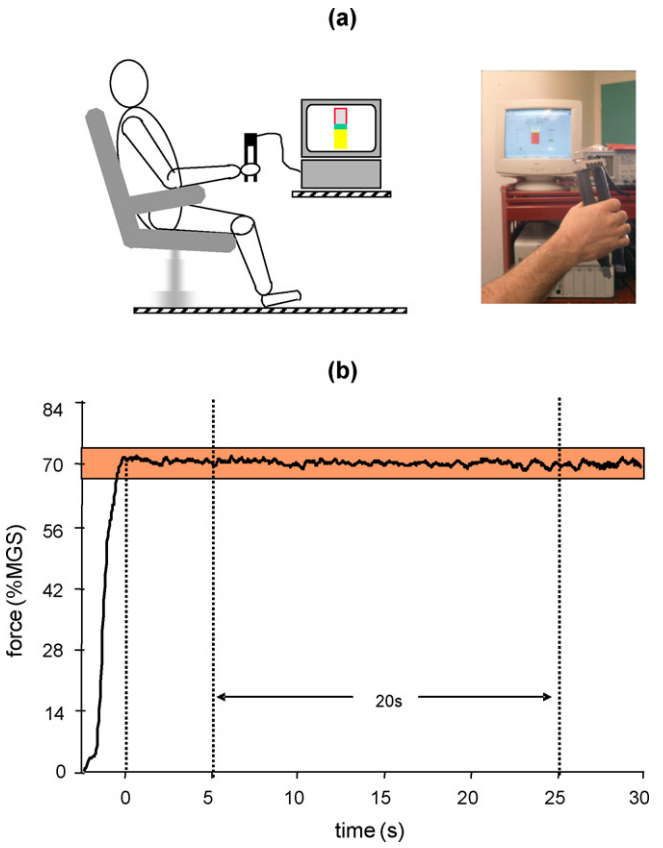

Fig. 1. (a) Position of the subject when gripping. The picture represents a subject gripping the MIE grip handle. (b) Results of sub-maximal grip-force test for a control subject. Data are normalized according to MGS. The light grey rectangle is the force target (from 67% to 73% MGS). The middle 20 s is the region selected for further analyses.
Reproduced in part with permission from [38].

2.3. Data collection

Grip force data were measured using an MIE grip handle (MIE Medical Research Ltd., Leeds, UK) with a resolution of 1 N and

Table 1
Subject characteristics for the four groups of subjects.

	GSD III		GSD V		MITO		Controls	
	Men	Women	Men	Women	Men	Women	Men	Women
n	7	8	8	7	9	5	10	8
Age (years)	27.6 ± 12.1	30.4 ± 14.7	42.3 ± 12.6	40.2 ± 14.1	39.4 ± 19.4	36.0 ± 11.5	38.8 ± 9.4	36.9 ± 7.9
Height (cm)	172.3 ± 14.4	167.9 ± 7.5	168.9 ± 4.8	163.1 ± 9.6	167.4 ± 5.2	159.4 ± 7.8	176.4 ± 3.0	163.0 ± 4.8
Weight (kg)	75.6 ± 19.6	64.3 ± 7.8	67.1 ± 6.0	60.7 ± 8.8	67.6 ± 15.8	53.4 ± 11.4	71.5 ± 4.7	62.5 ± 15.6
MGS (kg)	27.6 ± 13.8	20.2 ± 3.4	28.0 ± 5.0	23.9 ± 5.7	36.0 ± 10.7	17.7 ± 10.2	46.6 ± 7.3	30.8 ± 5.3

All data are presented as mean ± standard deviation.