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Linear and nonlinear analyses of multi-channel mechanomyographic recordings reveal heterogeneous activation of wrist extensors in presence of delayed onset muscle soreness

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ABSTRACT

In this study, we applied multi-channel mechanomyographic (MMG) recordings in combination with linear and nonlinear analyses to investigate muscular and musculotendinous effects of high intensity eccentric exercise. Twelve accelerometers arranged in a 3 × 4 matrix over the dominant elbow muscles were used to detect MMG activity in 12 healthy participants. Delayed onset muscle soreness was induced by repetitive high intensity eccentric contractions of the wrist extensor muscles. Average rectified values (ARV) as well as percentage of recurrence (%REC) and percentage of determinism (%DET) extracted from recurrence quantification analysis were computed from data obtained during static–dynamic contractions performed before exercise, immediately after exercise, and in presence of muscle soreness. A linear mixed model was used for the statistical analysis. The ARV, %REC, and %DET maps revealed heterogeneous MMG activity over the wrist extensor muscles before, immediately after, and in presence of muscle soreness ($P < 0.01$). The ARVs were higher while the %REC and %DET were lower in presence of muscle soreness compared with before exercise ($P < 0.05$). The study provides new key information on linear and nonlinear analyses of multi-channel MMG recordings of the wrist extensor muscles following eccentric exercise that results in muscle soreness. Recurrence quantification analysis can be suggested as a tool for detection of MMG changes in presence of muscle soreness.

1. Introduction

The first report of mechanomyographic (MMG) signals was published more than two centuries ago [1]. The physical origins of the MMG signal are the slow bulk movements of the muscle, the oscillations created by the muscle at its own resonance frequency [2,3], and the pressure waves due to muscle fiber dimensional changes [4]. Within the last decade studies of multi-channel MMG recordings have enabled a better understanding of the mechanical propagation of the MMG signal [5–8] as well as a better characterization of the MMG interference signal [9–11]. These studies have corroborated the dependency of the MMG signal to motor unit control strategy and muscle fiber membrane properties [4,12]. More specifically, multi-channel MMG recordings have been used in the study of spatial dependency, i.e., MMG maps assessing the spatial reorganization of MMG activity following conditional factors, such as intensity of contraction and muscle fatigue in the tibialis anterior, biceps brachii, erector spinae, and upper trapezius [8–11,13,14]. Multi-channel recordings enable a better estimation of the muscle forces [15]. The amplitude of the MMG maps increases gradually with the intensity of contraction [9–11]. In presence of muscle fatigue, the amplitude of the MMG maps increase over time [9,10]. In addition, MMG recordings are found complementary to surface electromyography as the MMG activity reflects muscular adaptations due to e.g., muscle pain and soreness [16–18].

Sports- or work-related elbow injuries are common [19]. For example, lateral epicondylalgia is a common elbow injury, with an annual incidence between 1–3% in the general population [20,21] and 0.4% of all visits to general practice [21,22]. In general, the diagnostic of lateral epicondylalgia is based on symptoms like tenderness and pain reported during a clinical examination despite the fact that imaging techniques can be useful [21]. The wrist extensors and more specifically the extensor carpi radialis brevis muscle, most likely plays an important role in the development of lateral epicondylalgia [23]. High intensity eccentric exercise results in delayed onset muscle soreness (DOMS) offering the possibility to study mechanisms related to elbow pain [24–26]. DOMS is

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suggested to occur due to the damage of muscle structure during the exercise and maintained by an inflammatory reaction in the muscle tissue [27,28]. The induction of DOMS in the wrist extensor muscles can be considered a valid model of lateral epicondylalgia, mimicking sensory changes reported in lateral epicondylalgia patients [24,25,29]. Using that model, sensory mapping of the wrist extensors has been performed in experimentally-induced and chronic lateral epicondylalgia [24,30]. But no study has assessed motor changes, i.e., MMG spatial changes in presence of DOMS in wrist extensor muscles.

An unexplored imaging technique related to wrist extensors is multi-channel MMG recordings. The technique has the potential to provide information about the spatial reorganization of MMG activity in experimentally induced lateral epicondylalgia. Recent findings have corroborated the presence of spatial heterogeneities in the MMG signal due to its complex structure [11,31–33] and non-stationary characteristic [34,35]. This can be explained by a non-linear summation of active motor units in the interference MMG signal [36]. Then, non-linear analytic methods like recurrence quantification analysis (RQA) [37–42] are likely to provide new insights on MMG changes in experimentally induced lateral epicondylalgia. We hypothesized that multi-channel MMG recordings will reveal heterogeneous distribution of the MMG activity of the wrist extensors in presence of DOMS.

2. Methods and materials

2.1. Subjects

The study was conducted on 12 healthy participants (eight males and four females) of mean age: 27.7 ± 6.5 years, body mass: 68.1 ± 10.3 kg, height: 176 ± 8 cm, and body mass index: 21.8 ± 2.1 kg/m^2. All participants, except two, were right-handed. The exclusion criteria were symptoms of musculoskeletal pain and complaints in the upper extremities within the last 12 months, regular intake of any medication, and participation in strength training involving the upper extremities. A physical examination was conducted to check that all participants had full pain-free range of elbow and wrist motion as well as no abnormal tenderness during palpation of soft tissues in the extensor muscles around the forearm and wrist. The participant population was identical to that in our recent study investigating pressure pain mapping after eccentric exercise [25]. Informed consent was obtained from all participants. The study was approved by the local Ethics Committee (N-20070004) and conducted according to the Helsinki Declaration.

2.2. Experimental protocol

The laboratory temperature was maintained at 22 °C. Participants were comfortably seated with their dominant forearm stabilized on a table. The forearm was pronated, the elbow was 60° flexed and the upper arm was 20° flexed. Prior to MMG recordings and eccentric exercise, the maximum voluntary contraction (MVC) was recorded in static conditions. The maximum wrist extension force was measured using a piezoelectric force transducer (Kistler type 9311A, Bern, Switzerland), hooked to a strap placed on the dorsal side of the hand over the distal part of the metacarpal bones. Three trials were made to determine MVC [24,25]. The highest (of three) MVC value was used as reference (100%) for determination of sub-maximal contraction levels during subsequent eccentric exercise (see below).

Second, 12 accelerometers were mounted on the skin, above elbow extensors of the dominant arm as described below (see Section 2.4). The MMG activities were collected while participants performed a standardized time-paced combination of static and dynamic contractions at sub-maximal levels (Fig. 1). The contractions started with a static contraction with the dominant wrist in a neutral position for 2 s (denoted isometric contraction). Then the participants performed a muscle shortening contraction to maximum wrist extension over 2 s (denoted concentric contraction), maintained their wrist at maximum extension for 2 s, performed a muscle lengthening contraction from maximum wrist extension to maximum wrist flexion over 2 s (denoted eccentric contraction), and finally maintained their wrist at maximum flexion for 2 s. Dumbbells of 1, 3, and 5 kg corresponding to, respectively, 6.3 ± 2.0%, 18.9 ± 6.1%, and 31.4 ± 10.1% of the initial MVC were used. The loads of the static–dynamic contractions were applied in a randomized order. The participants rested for 2 min between each static–dynamic contractions. After completion of the static–dynamic contractions, the rate of perceived exertion and the muscle soreness intensity were also collected (see Section 2.3).

Third, eccentric exercise was performed. This consisted of high intensity repeated eccentric wrist extensor contractions eliciting DOMS, following previously published procedures [24,25,29]. The sitting position was the same as the one described above. Eccentric exercise consisted of wrist movement from maximal extension toward maximal flexion over 4 s. The experimenter lifted the weight (over 1 s) to enable the next eccentric contraction starting from wrist maximal extension. All repetitions were performed at 90% MVC while the participants received verbal encouragement. In

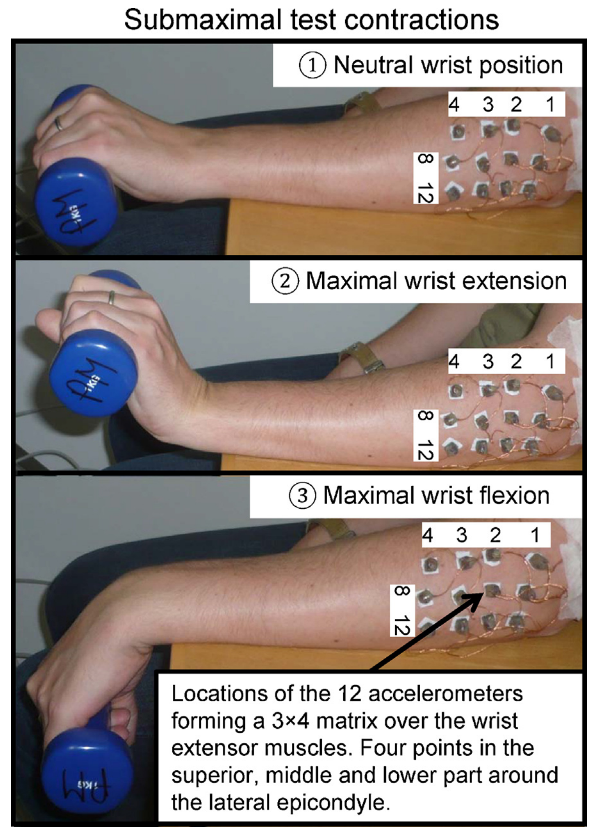

Fig. 1. Experimental setup for collecting MMG signals from the wrist extensor muscles during standardized sub-maximal static and dynamic contractions. Three types of contractions were analyzed: isometric (in position (1)), concentric (moving from position (1) to (2)), and eccentric (moving from position (2) to (3)). The contractions were time-paced and performed using loads of 1, 3, and 5 kg. MMG signals were recorded using 12 accelerometers forming a 3 × 4 matrix. Locations [1–4] represent the superior column and [4,8,12] the distal row.