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Muscular synchronization and hand-arm fatigue

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A B S T R A C T

Muscular fatigue occurs when motor units are no longer able to maintain an established force level. From an electromyographic point of view, fatigue is associated with a decrement of median frequency of contracting fibers. When the muscle is exposed to mechanical vibration, it undergoes a superimposition of voluntary contraction and stretch reflex, latter being synchronized to the mechanical frequency. The present paper is aimed to study the changes of muscular synchronization in long-lasting muscular tasks using a specific index change (ΔSL). Different frequencies of mechanical vibration (20, 30, 33, 40 Hz) and different levels of muscular task (20, 30, 40, 60% of the maximum) are studied by surface electromyography (sEMG) in prolonged exposures (t = 45 s). Results show a prominence of muscular synchronization (i.e. ΔSL) for a combination of force-frequency values at 30% MVC - 33 Hz. This is consistent but not identical with the behavior of other sEMG indicators of muscular fatigue, such as median frequency decay (MDF_d), as reported in literature, and suggesting that present results could better describe different aspects of the vibration stretch reflex. Using this knowledge may promote more effective vibrating tools for industry, oriented to reduce occupational fatigue. Since some force-frequency combination can stress the hand-arm system more than others, these results may help avoid work-related occupational injury.

1. Introduction

Hand-arm mechanical properties are responsible for transmissibility of vibration induced by externally powered tools maintained with the hand as sanders or drills. These occupational conditions are largely studied in order to prevent or minimize the occurrence of disease. On this regard, ISO standard frequency weighting curves (W_h) based on operator perception of mechanical vibration (MV) have been developed and are commonly used to define the hazard in occupational environments (UNI EN ISO 5349-1, 2004). In literature, several studies propose some changes to W_h in accordance with the use of special tools as breakers or rammers (Dong et al., 2005, 2006; Tominaga, 2005; Bovenzi, 2012). All those studies were based on a hand-arm purely passive mechanical model of the interaction tool-biological system but it is well known that the biological system is time changing as far fatigue and muscular fine adjustment. Conversely, studying the surface electromyography (sEMG) of the forearm during 45 s long hand-grip task has shown a changing behavior of the hand arm system when elicited by MV (Fattorini et al., 2016). This response shows the relationship between muscular fatigue and stimulus parameters (frequency and grip force). This relationship conflicts with the passive model; indeed, it shows a sEMG power varying with MV frequency and a relative increasing muscular fatigue with time. Recently Dong (Dong et al., 2012) proposed a factorization of the weighting curve that keeps into account with two factors the biodynamic and the biological components. The neuromuscular synchronization could be proposed as a third component.

For muscular fatigue assessments, from sEMG recordings, an index called Median Frequency decay (MDF_d) is used that represents the decrease of the median frequency over time. This decay has been related to muscular fatigue (De Luca, 1984; Merletti and Parker, 2004); which showed a relative maximum of neuromuscular fatigue at a proper combination of MV force and frequency (i.e. the 30% of maximum and 33 Hz respectively) compared to the

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absence of MV using MDF_d (Fattorini et al., 2016). They argued that this could be due to changes in articular stiffness induced by the muscular contraction. It is self-evident that in usual working conditions tools are handled for prolonged time, so the onset of muscular fatigue will be very likely. Moreover, as postulated in (Fattorini et al., 2005), muscular recruitment pattern would change if elicited by a MV for a long time. Studying the same phenomenon, Martin and Park (1997) proposed an index, derived from sEMG, to account for the quantity of muscular recruitment synchronized with MV: the normalized synchronization index (SL). This index is related to the sEMG power around MV frequency divided by the total sEMG power, and it takes into consideration that a repetitive stimulus may induce a neuromuscular response with similar frequency characteristics of MV. This is because the stimulus elicited a mono-synaptic loop from skin mechanoreceptors and muscular fibers, which is known in physiology as a reflex arc and in this particular case, as the Tonic Vibration Reflex (TVR).

As stated above, (Fattorini et al., 2016) showed that the change of MDF_d was a consequence of MV. The MDF_d is the frequency that divides in two the EMG power spectrum and is a parameter that reveals the change in muscle recruitment pattern, but it is unfit to explain the reason of such changes. On the other hand, the SL is a parameter that is related to the muscular response to the MV only; and, although it is unsuitable to detect the muscular fatigue, it could reveal if muscle activation is modified by the MV.

Thus, present study is aimed to assess the muscular response to MV over time (i.e. TVR changes) in prolonged hand-grip task with different MV frequencies. As a TVR index it will be used the SL index and, given its characteristics, it will be compared with other sEMG parameters present in literature.

Present findings could be useful to characterize specific occupational situations that may induce an early muscular fatigue or a neuromuscular inefficiency and result in work injury. For this reason a standard experimental condition has been adopted similar to those met in the field.

2. Materials and methods

2.1. Experimental design

The experimental setup has been shaped to assess the muscular activity, for a prolonged time, while the subject was exposed to mechanical vibration as he performed a specific motor task. This setup needed the standardization of multiple aspects, which are detailed in the following paragraphs.

The general description of the setup is as follows: the subject had a given posture, typical of most working conditions, and was exposed to mechanical vibration of different given frequencies. He/she had to hold posture and force level for the duration of the experiment. The sEMG signal of two muscles of the forearm was recorded for an extended duration of time, in order to acquire the signal of a fatiguing muscle. For each subject all measurements were performed on the same day, so it was needed and granted adequate rest-time between sessions. The study was conducted according to the declaration of Helsinki and followed the guidelines established by the ethics committee of the University Sapienza of Roma and the indications of INAIL.

From the sEMG signal the difference of synchronization of the late motor task signal minus the early motor task signal (ΔSL) and the median frequency decay (MDF_d) was analyzed.

2.2. Subjects

Thirty-four experimental subjects have been selected from healthy volunteers: 16 females and 18 males (age 22 ± 5 years, weight 70 ± 11 kg, height 1.73 ± 0.08 m). None of the subjects had history of muscular or bone injuries, diseases, nor previous professional exposure to vibration. All subjects signed a preliminary informed consent to the experiment.

2.3. Vibration signals

Mechanical vibration exposure was provided by a handle (first resonant frequency at 800 Hz) linked to the electrodynamic shaker (RMS SW 1508, Germany, EU). The shaker was driven by a controller (Vibration Research VR 7500-2, Germany, EU) at 20, 30, 33 and 40 Hz. The vibration control loop was closed by an accelerometer (PCB, 353M197, NY, USA) on the baseplate of the handle. The signal had a constant velocity amplitude of $27 \cdot 10^{-3}$ ms^{-1}. The sequence of vibration imposed to the handle was randomly administered to each subject.

2.4. Motor task

The motor task consisted of holding with the dominant hand (subjects' declaration) the instrumented handle at a pre-established force values for at least 45 s with a prefixed grip force. The handle had strain gauges for grip force measurement (Fig. 1). To measure both components of grip force (i.e. push and pull) the handle is divided in two halves, connected by bridged strain gauges. This configuration allowed, both, zeroing the Wheatstone bridge before every measurement and continuous checking of push and pull forces. Temperature and humidity conditions, having great influence over strain gauge response, were kept stable during measurements with air conditioning.

The grip force exerted was expressed in terms of percentage of Maximum Voluntary Contraction (MVC). The MVC was the maximal force exerted on the handle over three repetitions, each lasting 5 s. The MVC value adopted was the highest of these reiterations. The force values requested during the motor tasks were 20–30–40–60 percent of MVC. Both components of grip force were continuously recorded and displayed to the subject by an oscilloscope (Hewlett & Packard, 54603B, CA, USA) to help maintain the given level of force and balancing between push and pull (see Fig. 1). Absolute grip forces (balancing push and pull) were in the range 220–800 N. After each measure the subject was given a rest period of 15–30 min, depending on the force exertion during the test.

2.5. Subject posture

The subject's forearm was directed along the shaker axis defining the Z axis (Fig. 1). The elbow formed an angle of 90°, and did not to touch the body during the measurements. This posture was standardized following the (UNI EN ISO 10819, 1998) for glove testing. The subject was asked to stand upright, on an adjustable

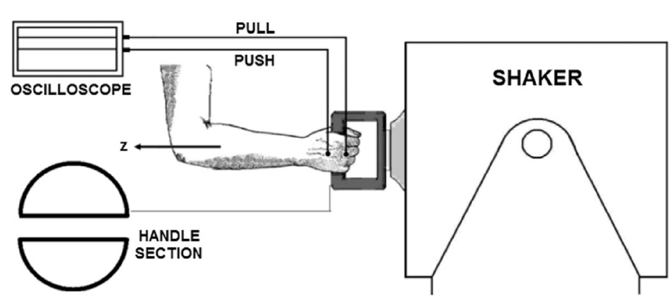

Fig. 1. Posture and experimental setup.

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