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Nonlinearity of Power Absorption Curve and Hand-Arm System Physiology †

Enrico Marchetti [1,*], Luigi Fattorini [2], Marco Tarabini [3], Raoul Di Giovanni [1], Massimo Cavacece [4] and Angelo Tirabasso [1]

[1] INAIL, DIMEILA, Laboratory Physical Agents, 00078 Monte Porzio Catone, Italy; r.digiovanni@inail.it (R.D.G.); a.tirabasso@inail.it (A.T.)
[2] Department of Physiology and Phamracology «V. Erspamer», Università Sapienza di Roma, 00185 Rome, Italy; luigi.fattorini@uniroma1.it
[3] Department of Mechanical Engineering, Politecnico di Milano, 20156 Milano, Italy; marco.tarabini@polimi.it
[4] Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, 03043 Cassino, Italy; cavacece@unicas.it
* Correspondence: e.marchetti@inail.it; Tel.: +39-0694181584
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Abstract: Models of hand–arm systems (HAS) are purely mechanical. These models do not include the biological active behaviour of the system, even though it has been known since 1997 that there is a tonic vibration reflex. Since then, several authors have investigated this reflex and related it to grip force, posture and some others features of mechanical vibration power absorption. Other scholars proposed models of HAS that do not include the tonic vibration reflex and its consequences. These models, even partial models, are nonetheless effective in describing many aspects of vibration exposure. This is probably due to the complexity of the HAS, so that the confounding factors overwhelm measurements.

Keywords: power absorption; hand–arm; mechanical vibration; synchronization; tonic vibration reflex; muscular fatigue

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1. Introduction

The power/energy of mechanical vibration absorbed by the hand–arm system (HAS) has been studied since the early 1970s, as this energy supposedly contributes to the eventual damage in the HAS. Mathematical models are a common way to better study the input–output relationship in complex systems but also in HAS investigations. In this regard, many authors have assessed the nonlinearity in different conditions and there are some attempts to explain this nonlinearity via the involvement of mechanical and physiological schemes. On the other hand, while studying models of the HAS, this nonlinearity is usually disregarded. The model benefits are related to the forecast of energy absorption by the HAS when exposed to a determined spectrum of mechanical vibration. Therefore, this nonlinearity should be included in models, particularly because the lack of linearity suggests the action of a physiological active mechanism which may be connected with the insurgence of vibration pathology. Nonetheless, the lack of inclusion of muscular synchronization does not affect the model's effectiveness.

This paper was written to point out this fact as well as the need to better understand nonlinearity in power absorption, taking its many features into account.

2. Hand–Arm System Vibration Biodynamics

The first biodynamical study of HAS was dated in 1972 with the work of Reynolds [1]. Radwin et al., in 1987, studied the interaction of grip force and frequency of mechanical vibrations, finding an influence of the frequency stimulus on grip force [2]. This suggested that the muscular activity alters the pattern of force production, both for a spinal response tonic vibration reflex (TVR), and for a motor drive modification involving superior motor areas. Successively, in 1994, Burstrom and Lundstrom [3] improved the measurement and definition of observables related to the biodynamic behaviour of the HAS. In their work, the authors pointed out that the main experimental conditions influencing measurements were the vibration direction, the grip force, the vibration level, the hand–arm posture and the constitution of hand and arm. The work of Martin and Park in 1997 [4] highlighted the TVR and proposed an electromyographical measurement standard for assessing the TVR influence in the normalized synchronization index SYNC, both within vibration frequency and far from it. The authors also suggested the hypothesis that synchronization could affect muscle fatigue. After this study, it is difficult to avoid considering physiology as part of the study of the HAS response to mechanical vibrations.

More recently, other works considered the relation between TVR, grip force and fatigue [5–9]. The findings of these papers were that muscular fiber's synchronization on the external vibration frequency probably increased muscular fatigue. The reason must be sought in the muscular response driven by the stretch reflex, i.e., the muscular contraction induced by the variations detected by muscular spindles and the Golgi tendon's receptors. This reflex allows the fibers that have a firing frequency near that of the vibrational one to contract more often than the other. This implies that there are some fibers that do not have rest, while there are others that not affected by the vibration. Evidently, neuromuscular systems have to satisfy two motor tasks: grip force production and TVR. For this, a capacity reduction to maintain a force level is expected, and this mechanism is the basis of muscle fatigue from a physiological point of view. The synchronization and the fatigue have been measured upon varying the posture and the grip force, while the direction and the level was fixed. Individual constitution was taken into account, comparing relative grip force to individual maximum voluntary contraction (MVC). The suggestion of the synchronization being a motion artifact was definitely rejected after the paper of Ritzman et al. [10].

The finding of this line of research is that absorption of vibration energy does affect muscular fatigue.

3. Models of HAS

Notwithstanding the lack of implementation of the aforementioned characteristics, models of HAS have been generated from 1972 [1] to the present day [9]. Models of HAS include linear and nonlinear characteristics [11] in order to mitigate vibration exposure deriving from handheld power tools [12] or from rig construction [13]. A noteworthy review of the work of NIOSH in that respect is the paper from Dong et al. [14].

Models are useful tools for the prediction of the HAS response to vibration exposure and they work efficiently in that sense, even without the implementation of physiological nonlinearity; the latter could help model muscular fatigue in the physiological definition, i.e., the inability to hold the muscular task for extended periods.

In general, the lack of the fatigue and physiological elements imply that models are representative of the HAS response for limited exposure times and for forces that are small (as percentages of the MVC).

4. Muscle Fatigue Measurement

The experiments described in this paper share the setup of another abstract—Interference of vibration exposures in the force production of the hand–arm system—and are designed to test the effects of muscular fatigue. Subjects are required to grip a handle with forces equal to 30% and 60% of MVC. Grip force is the result of two opposing components: push and pull. The subject was able to confirm both push and pull force and was required to balance it as close as possible to zero while keeping the prescribed grip force. Participants were exposed to vibration with a frequency of 30 Hz and amplitudes of 5–7.5 and 10 m/s^2. The effect of fatigue was analyzed by measuring the length of time for which participants could maintain the desired grip force.

Present results (summarised in Tables 1 and 2) show a limited influence of vibration on the time for which the subject could endure the motor task. Some subjects even improved their endurance under vibration, while some others shortened it.

Table 1. Time of endurance in minutes of a motor task of 30% of MVC upon varying the handle vibration.

	No Vib	**5 m/s^2**	**7 m/s^2**	**10 m/s^2**
1	4.53	5.10	4.75	5.03
2	5.02	5.04		
3	3.40	2.26		
4	4.35	5.12	4.02	3.55
5	4.48	3.40	3.38	4.70

Table 2. Time of endurance in minutes of a motor task of 60% of MVC upon varying the handle vibration.

	No Vib	**5 m/s^2**
1	1.28	1.35
2	2.01	1.00
4	0.45	1.14
5	2.40	2.02

5. Conclusions

The experiments did not evidence a significant effect of the vibration on the time for which participant could keep the MVC. Results are consistent with those of other laboratory works [15,16] in which muscular synchronization and muscular fatigue were not evident.

The conclusion is that there are some active mechanisms that intervene in the contraction while exposed to vibrations and that those mechanisms have to be studied in depth before we can obtain complete knowledge of muscular synchronization and fatigue. In other works, we encourage a larger collaboration between vibration experts and physiologists to overcome the current lack of specific knowledge on the effect of fatigue on the HAS response.

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