Proceedings of the 29th Annual International
Conference of the IEEE EMBS
Cité Internationale, Lyon, France
August 23-26, 2007.

SaC09.4

Electromyographic hyperactivation of skeletal muscles by time-modulated mechanical stimulation

Massimo Mischi, *Member, IEEE,* and Irene Kaashoek

Abstract— **Current skeletal muscle conditioning is typically performed by application of a steady force (load). However, as confirmed by whole-body-vibration applications, the involvement of neuromuscular reflex due to load variations plays an important role in muscular conditioning. Therefore, in this paper we present a prototype for muscular conditioning where the loading force, which is generated by an electromagnetic actuator, is modulated over time during the exercise. The force modulation is controlled by a dedicated control unit implemented on a personal computer. The determination of the transfer function of the mechanical transmission to the user confirms that the force modulation is efficiently transferred up to 40 Hz. A preliminary validation involved the electromyographic analysis of the muscle activation. A 29 Hz sinusoidal force modulation around different baseline loads was applied to both biceps and triceps of 12 subjects. Force modulation resulted in the hyperactivation of the muscle electrical activity, which was estimated as the root mean square of the electromyogram, for all baseline loads ranging from 20 to 100 % of the maximal voluntary contraction. These promising results confirm the important role of reflex for optimal muscle training and motivate further research to realize a dynamic load control based, for instance, on electromyographic features.**

I. INTRODUCTION

Current methods for skeletal muscle conditioning in fitness and rehabilitation are resistance training, where a mechanical load is applied to specific muscles, and whole body vibration (WBV), where a vibration with a fixed frequency and waveform is applied to the whole body. Muscle conditioning is the result of physiological adaptation processes induced by the training stimuli. The first muscle adaptation is a neural adaptation. In regular training, this occurs within a few months. Adaptations of the morphological structure of the muscle take much longer [1].

Resistance training involves the use of either passive machines, in which different force levels can be selected by loading different weights, or electro mechanical machines, in which a load is generated by an electromagnetic actuator. This training method can target any specific muscle group. A limitation of this training strategy relates to the need of high loads, typically inducing more than 75 % of the maximal voluntary contraction (MVC), in order to obtain a substantial recruitment of muscle fibers and, therefore, to train neuromuscular coordination and maximal strength. In the deltoids, for instance, a maximal recruitment of fibers is reached beyond 80 % of the MVC [2]. The number of recruited fibers is proportional to the force produced by the muscle and it is typically correlated to the root mean square (RMS) of the electromyogram (EMG), i.e., the electrical signal that is measured from the muscle fibers [3], [4].

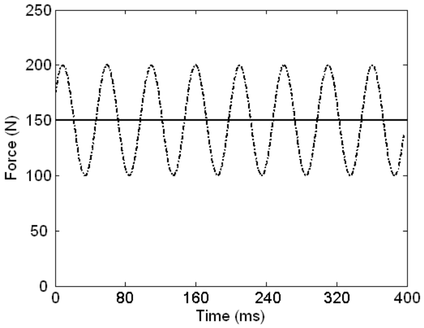

Fig. 1. Example of sinusoidal force modulation at 20 Hz with an amplitude of 50 N (dashed line). The 150 N baseline load is also shown (solid line).

In WBV the body is subjected to a high frequency vibration (typically between 25 and 50 Hz) of the platform where it stands. The vibration consists of the relative displacement (few millimeters) between the left and right side of the platform, typically produced by eccentric electrical motors. As proven in previous studies, the use of high frequency vibrations may result in increased uptake of oxygen and glucose, bone density, and secretion of hormones such as growth hormone, serotonin, and testosterone [5]–[7]. The major results concern however improvements in muscle strength and coordination [1]. This could be expected due to the relevance of neuromuscular adaptation processes in the improvement of maximal strength and coordination of fiber recruitment [5]. An important stimulation to the neuromuscular system is in fact the major characteristic of WBV training, as also confirmed by electromyographic measurements in the leg extensor (vastus lateralis) [8].

Despite its simplicity, a significant limitation of this training device consists of the poor control on the major training parameters. The force applied to the body depends on the body weight and the acceleration due to vibration. As a result, the force is also dependent on the vibration frequency.

The interesting training effects of WBV together with its limitations motivated us to develop a novel prototype for muscular training, where all the major training parameters can be independently controlled. Instead of generating and imposing a displacement in order to apply an acceleration-dependent force, we directly control and modulate the force generated by an electromagnetic actuator. An example of sinusoidal force modulation at 20 Hz with an amplitude of

---

This work was supported by the Dutch Foundation for Technology STW.

M. Mischi and I. Kaashoek are with Faculty of Electrical Engineering, Eindhoven University of Technology, the Netherlands. Contact: `m.mischi@tue.nl`

1-4244-0788-5/07/$20.00 ©2007 IEEE

50 N and a baseline load of 150 N is shown in Figure 1. In contrary to WBV, different mechanical designs allow training different muscles.

In this study, we present and validate a prototype for arm muscle conditioning. The force modulation is fully controlled by computer. Specific measurements were performed that proved the capability of the whole system to produce an efficient force modulation up to 40 Hz.

As shown in Figure 1, the sinusoidal force modulation is superimposed to a baseline load. During the modulation peaks, the load can be significantly higher than the baseline, therefore inducing the recruitment of more muscle fibers. However, the time duration of these stimuli is very short and they can be easily sustained by the user. In fact, similarly to WBV training, this type of force modulation, which is faster than voluntary control mechanisms, involves neuromuscular reflex. Neuromuscular reflex is therefore the main mechanism through which such a stimulation is processed by the neuromuscular system to control muscle contraction and relaxation.

A preliminary validation of the force modulation effects on the muscles was performed by means of the analysis of the surface electromyogram (sEMG). Measurements on biceps and triceps of 12 volunteers were performed for baseline loads inducing from 20 to 100 % of the MVC with and without force modulation. The root mean square (RMS) of the sEMG was used as an index of the muscular activation level. The results show an electrical hyperactivation, i.e., a higher RMS of the sEMG, in the presence of a modulated force for all the MVC percentages.

II. METHODOLOGY

In order to provide an overview of the physiology related to the mechanical muscle stimulation presented in this study, in section II-A the major aspects of neuromuscular reflex are shortly reported. Then, in section II-B, the developed prototype for muscle conditioning is described and characterized. Finally, in section II-C, the measurement setup and protocol for sEMG analysis is presented.

A. Neuromuscular control

In the skeletal muscles there are several different receptors that continuously monitor the state of the muscle. The muscle spindle, which is situated between the muscle fibers, measures the muscle length and its rate of change. This information is transmitted through Ia afferent neurons, which are directly connected to the motor neurons that control the muscles. This feedback loop is used in the stretch reflex: when a muscle is stretched, the motor neurons make the muscle contract to oppose to the stretching [9]. This is referred to as monosynaptic reflex, as only one synapsis (from the group Ia afferent to the motor neuron) is involved. However, the group Ia afferents have also multiple connections to interneurons. These connections are at the basis of polysynaptic reflexes, which control for instance the coordination and the reciprocal inhibition between antagonist muscles.

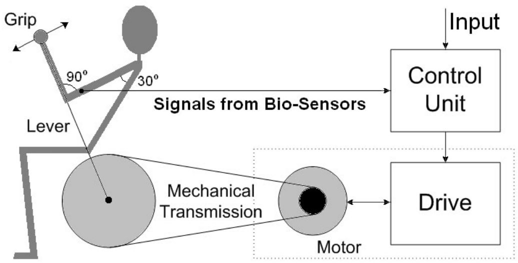

Fig. 2. Schematic representation of the prototype for time-modulated mechanical stimulation of biceps and triceps.

The neuromuscular activity can be stimulated when sudden variations of the mechanical load to the muscle occur. An extreme case is the use of vibrations or force modulation. Mechanical vibration applied to a muscle (or its tendon) excites reflex muscle contractions due to the length variation. The muscle tries to stabilize the joint by damping the vibration [1], [10]. This phenomenon is referred to as tonic vibration reflex (TVR). TVR consists of an increase of motor unit recruitment due to activation of muscle spindles, mediation of the signals by Ia afferents, and activation of muscle fibers via large α-motor neurons [1].

TVR is a rather complex phenomenon, which is not completely understood. It is caused by mono- and polysynaptic reflexes, but the exact pathway is not known. The Ia spindle afferents seem to stimulate impulses following a polysynaptic excitatory pathway and a presynaptic inhibitory pathway [11]. The first is responsible for the TVR while the latter inhibits vibration-induced reflexes. This is referred to as vibration paradox. The inhibition is dependent on the vibration amplitude rather than the vibration frequency [12]. The excitatory component is however dependent on the vibration frequency. The importance of an independent control on the stimulation parameters (amplitude and frequency of the force modulation) appears therefore clear. Studies based on the use of WBV proved that the maximum RMS of the EMG measured on the leg vastus lateralis is obtained for vibration at about 30 Hz [10].

B. Force modulation prototype

The general scheme of the prototype is shown in Figure 2. The main components are an electromagnetic actuator (comprising electrical motor and drive), a mechanical transmission, bio-sensors, and a control unit.

The electromagnetic actuator is an industrial permanent magnet motor (MSK060C Rexroth IndraDyn®) controlled by a dedicated drive (Rexroth IndraDrive®). The drive receives an input with an arbitrary voltage waveform from a control unit that is implemented on a personal computer. This control unit is implemented in LabView® (National Instruments) and it controls a PCI-5402 wave generator (National Instruments) that applies the input voltage to the motor drive. The drive supplies a current to the motor and receives position information from the motor.

The control unit can receive inputs from the user or from selected bio-sensors in order to optimize the loading

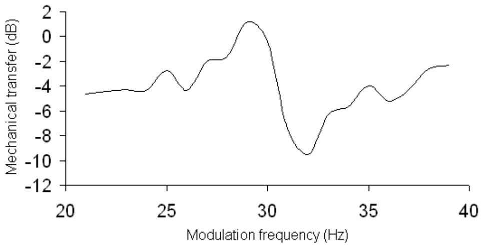

Fig. 3. Transfer function of the mechanical transmission between 21 and 40 Hz.

function. Among the possible bio-sensors, sEMG electrodes are a suitable option to assess the muscle condition and activation [3], [10].

The mechanical transmission transfers the force generated by the motor to a rotating lever, which applies the force to the muscles. The rotation ratio from the motor to the base of the lever is 128. Since the lever is 130 cm, the resulting maximum peak force at the grip (lever handle) is larger than 2000 N. In static conditions, the linear relation between the input voltage to the motor drive and the force at the grip has been experimentally verified. The correlation coefficient up to 500 N was equal to 0.999.

In dynamic conditions, the mechanical transmission introduces a damping that attenuates part of the generated force modulation amplitude. The mechanical transmission can be modeled by a sixth order linear system, however, for an accurate determination of the transfer function, experimental dynamic measurements were performed in the frequency range between 21 and 40 Hz, which is reported to be the most effective for WBV [10].

The transfer function of the mechanical transmission was identified by measuring the angular acceleration of the motor shaft and the base of the lever during a frequency sweep ranging from 21 to 40 Hz (Figure 3). The motor acceleration was measured by the motor drive encoder while the acceleration at the lever was measured by an optical rotary encoder (Sick Stegmann HG600) with a resolution of 10.000 pulses/rotation. Part of the mechanical transmission uses elastic belts, resulting in resonances at low frequencies (below 20 Hz) and increased damping at higher frequencies (above 40 Hz).

Since the transmission shows a resonance at 29 Hz (Figure 3) and this frequency is close to the values that are most effective for muscle activation [10], this frequency was chosen to test the effect of force modulation on the electrical activity of the muscles. The determination of the amplitude of the force modulation is however critical. This amplitude is determined by the amplitude of the sinusoidal waveform at the motor drive input. In this study, this amplitude was set to 1.2 V. Combining the measurement results on the static relationship between input voltage and output force and on the mechanical transfer function, 1.2 V corresponds to an amplitude of the modulation equal to 492 N.

C. Measurement setup

12 Subjects (7 females and 5 males with ages varying between 20 and 27 years) performed independent isometric contractions of the biceps and triceps of the right arm at 20, 40, 60, 80 and 100 % of their MVC. The frontal elevation of the elbow was 30 degrees and the elbow angle was 90 degrees (Figure 2). These contractions, which lasted 15 s each, were performed without and with 29 Hz sinusoidal force modulation.

During these contractions, the sEMG of the biceps and triceps was measured by electrode pairs in a bipolar configuration. The electrode pairs were placed along the fiber direction between the tendon (at the elbow side) and the muscle belly. Circular Ag-AgCl electrodes of 1 cm diameter were used. The inter electrode distance was 2 cm. Especially for low conduction velocities of the motor unit action potentials (fiber depolarization), larger distances between the electrodes would introduce a stop-band filter in the bandwidth of interest [3]. The signals were amplified and digitized at 2048 Hz by a Mobi8 amplifier (TMS International), which transmitted the measured data to a personal computer by bluetooth® wireless technology.

For each contraction, the time interval between 2 and 8 s was processed for the sEMG analysis. The sEMG signal was preconditioned by a finite impulse response (FIR) band-pass filter with low and high cut-off frequencies equal to 18.3 Hz and 500 Hz [3].

In order to assess the electrical activity of the muscle, the RMS was calculated on the selected time intervals for each subject and each MVC percentage. Although the RMS is commonly adopted to estimate the muscle electrical activity [4], [10], [13], alternative approaches make use of the average value of the rectified signal [14]. As the difference is typically minimal [3], in this study we focused our analysis on the RMS evaluation.

The results could be affected by electromagnetic interference due to coupling with the large intensity currents that are fed to the electromagnetic actuator. However, as a result of the active shielding and grounding of the measurement system, the electromagnetic interference was proven to be either absent or negligible.

III. RESULTS

A summary of the results of the sEMG analysis with and without force modulation on 12 volunteers are reported in Figures 4 and 5 for the biceps and the triceps, respectively. All the values are normalized with respect of the RMS measured at 100 % of the MVC without force modulation. In both muscles an increase of the sEMG RMS can be noticed for MVC ranging from 20 to 100 % when force modulation is applied. This increase is however more evident in the biceps.

Table I reports the average RMS increase for all the MVC percentages when force modulation is applied. The standard deviation and the statistical significance of the estimates is also shown. The significance is derived by the Student t-test.

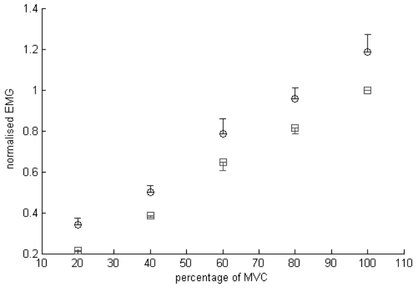

Fig. 4. Mean normalized sEMG RMS measured on the biceps of 12 subjects. The squares and the circles indicate the results without and with modulation, respectively.

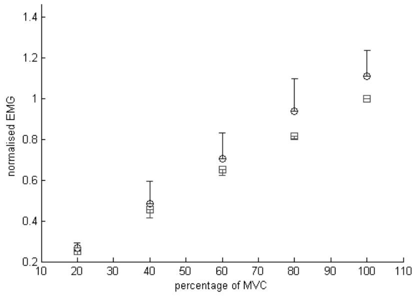

Fig. 5. Mean normalized sEMG RMS measured on the triceps of 12 subjects. The squares and the circles indicate the results without and with modulation, respectively.

IV. DISCUSSION AND CONCLUSIONS

A prototype that is able to apply a modulated force to the skeletal muscles up to a frequency of 40 Hz is presented. The loading function is generated by an electromagnetic actuator that is fully controlled by a personal computer. According to the torque transfer characterization and the results reported in the literature for WBV, a frequency of 29 Hz was chosen to test the effects of (sinusoidal) force modulation on the electrical activity of the muscles.

The estimated amplitude of the adopted force modulation (492 N) was such that for lower baseline loads an inversion of the motor rotation should occur. However, the estimated transfer function of the mechanical system did not account for the inertia of the user (unloaded lever), showing resonances that might not appear in the real application. Future work should therefore include the evaluation of the transfer function by means of a torquemeter.

The sEMG in the biceps and triceps of 12 volunteers was measured and analyzed. The resulting RMS shows a clear electrical hyperactivation of the muscles in the presence of force modulation for different percentages of MVC. These effects are more evident in the biceps. A comparable hyperactivation could be also assessed after excluding the modulating frequency component from the RMS computation, proving that motion artifacts did not affect the analysis. Further investigation is however necessary to identify the nature of the energy measured at the modulating frequency.

Although this study was performed with a 29 Hz force modulation, the developed prototype allows testing the effects of different frequencies. Such a study could permit the determination of optimal frequencies for different training objectives, so that not only the neuromuscular stimulation, but also the stimulation of the muscle metabolism (e.g., oxygen or glucose uptake), could be considered. The flexibility of the presented prototype will also allow the investigation of the muscle conditioning effect of modulating waveforms that are different from the adopted sinusoidal function. Eventually, the acquired insight could permit the implementation of a dynamic adaptation of the loading function based on the measurements from specific sensors, such as the electrodes used in this study.

TABLE I

sEMG RMS PERCENT INCREASE DUE TO FORCE MODULATION

MVC	biceps (significance)	triceps (significance)
20%	161% ± 80% (98%)	116% ± 64% (75%)
40%	133% ± 43% (98%)	105% ± 40% (70%)
60%	130% ± 57% (90%)	112% ± 60% (70%)
80%	118% ± 19% (99.5%)	116% ± 42% (85%)
100%	119% ± 30% (95%)	110% ± 36% (80%)

REFERENCES

[1] S. Torvinen, P. Kannus, H. Sievanen, *et al.*, "Effect of 8-month vertical whole body vibration on bone, muscle performance, and body balance: A randomized controlled study," *Journal of Bone and Mineral Research*, vol. 18, pp. 876–884, 2003.

[2] C. DeLuca, R. Lefever, M. McCue, and A. Xenakis, "Behaviour of human motor units in different muscles during linearly varying contractions," *J. Physiol.*, vol. 329, pp. 113–128, 1982.

[3] R. Merletti and P. Parker, *Electromyography. Physiology, Engineering and Noninvasive Applications*, S. V. Kartapoulos, Ed. John Wiley & Sons, Inc., Hoboken, New Jersey, 2004.

[4] C. Westad and R. Westgaard, "The influence of contraction amplitude and firing history on spike-triggered averaged trapezius motor unit potentials." *Journal of Bone and Mineral Research*, vol. 562, no. 3, pp. 965–975, 2005.

[5] C. Delecluse *et al.*, "Strength increase after whole-body vibration compared with resistance training." *Medicine and Science in Sports & Exercise*, pp. 1033–1041, 2003.

[6] S. Verschueren, M. Roelants, C. Delecluse, S. Swinnen, D. Vanderschueren, and S. Boonen, "Effect of 6-month whole body vibration training on hip density, muscle strength, and postural control in postmenopausal women: A randomized controlled pilot study." *Journal of Bone and Mineral Research*, vol. 19, no. 3, pp. 1033–1041, 2004.

[7] C. Bosco, M. Lacovelli, O. Tsarpela, *et al.*, "Hormonal responses to whole-body vinbration in men." *Eur J Appl Physiol*, vol. 81, 2000.

[8] C. Bosco, M. Cardinale, and O. Tsarpela, "Influence of vibration on mechanical power and electromyogram activity in human arm flexor muscles," *Eur. J. Appl. Physiol. Occup. Physiol.*, 1999.

[9] A. Guyton and J. Hall, *Textbook of Medical Physiology*, 11st ed. Elsevier Saunders, 2006, chapter 54.

[10] M. Cardinale and J. Lim, "Electromygraphy activity of vastus lateralis muscle during whole-body vibrations of different frequencies," *J. Strength Cond. Res.*, vol. 17, no. 3, pp. 621–624, 2003.

[11] J. Burke, M. Schutten, D. Koceja, and C. Kamen, "Age-dependent effects of muscle vibration and the jendrassik maneuver on the patellar tendon reflex response," *Arch Phys Med Rehabil*, vol. 77, no. 6, pp. 600–604, 1996.

[12] B. Martin, J. Roll, and G. Gauthier, "Inhibitory effects of combined agonist and antagonist vibration on h-reflex." *Aviat. Space Environ. Med.*, vol. 57, no. 7, pp. 681–687, 1986.

[13] R. Bluthner, H. Seidel, and B. Hinz, "Myoelectric response of back muscles to vertical random whole-body vibration with different magnitudes at different postures." *Journal of Sound and Vibration*, vol. 253, no. 1, pp. 37–56, 2002.

[14] M. Solomonow, R. Baratta, B. Zhou, and R. D'Ambrosia, "Electromyogram coactivation patterns of the elbow atangonist muscles during slow isokinetic movement," *Experimental neurology*, vol. 100, no. 3, pp. 470–477, 1988.