A Lumped Parameter Model for the Analysis of the Motion of the Muscles of the Lower Limbs under Whole-Body Vibration

F. Amato, P. Bifulco, M. Cesarelli, D. Colacino, C. Cosentino, A. Fratini, A. Merola, and M. Romano

Abstract—**Through a lumped parameter modelling approach, a dynamical model, which can reproduce the motion of the muscles of a human body standing in different postures during Whole Body Vibrations (WBVs) treatment, has been developed.**

The key parameters, associated to the dynamics of the motion of the muscles of the lower limbs, have been identified starting from accelerometer measurements.

The developed model can be usefully applied to the optimization of WBVs treatments which can effectively enhance muscle activation.

I. INTRODUCTION

THE interest on vibratory stimulation has risen in the last decades for the capacity of mechanical oscillations to elicit muscular responses. It is known in fact that a reflex muscular contraction, the Tonic Vibration Reflex (TVR), is produced via physiological pathways during vibratory stimulation of tendons or muscles [1].

Local vibratory stimulation has rapidly been extended to the whole body, as a mean of complete body stimulation, through the use of vibrating platforms. These devices produce mechanical oscillations in a frequency range of about 10 to 80 Hz and peak to peak amplitudes of 1 to 10 mm [2]. The mechanical stimulus reaches different target muscles depending on the specific postures assumed by subjects standing on the platform [3].

Literature examples are concentrated on lower limbs muscles particularly on the enhancement of muscular performances in elite athletes [4]-[6]; however, other positive effects have been reported for bone mineral density and cardiorespiratory system activation increase [7][8].

Vibratory stimulations effects are generally revealed using the analysis of modification in electromyography (EMG) recordings leading, to some extent, in overestimating the actual stimulation effects [9],[10].

Recent studies combined the use of filtered EMGs with the analysis of muscles motion under whole body mechanical oscillations [11] and the findings pointed out that muscle activation is maximized at resonance frequency.

Specific modelling has been developed to analyse resonance of body segments and muscles at different conditions (postures and frequencies) [3] but further studies are needed to achieve a more complete understanding of biomechanical response of body subjected to mechanical oscillations.

This work aims to develop a preliminary lumped parameter model for the analysis of muscles motion during a vertical whole body vibration session. In particular, the authors intended to replicate the dynamics of mechanical response of quadriceps of a subject standing on a vibration platform by using actual accelerometer experimental data.

II. METHODS

A. Model description

A lumped parameter model of the dynamics of the muscles of the legs during whole-body vibration treatment for a subject in standing position has been developed.

The model structure has been chosen as one the minimal configurations able to fit the time profiles of the principal components of the muscle motion, which are experimentally measured.

The structure and the dynamic response of the human body, in upright standing position and exposed to vertical whole-body vibration, are described resorting to the seven-degree-of-freedom mechanical model by Subashi et al. [12]. The model can reproduce the vibration modes of the body at different postures in which a subject bent their legs at the knees. The model structure is constructed through the interconnection of lumped masses, representing the inertial properties of the musculoskeletal structure, and some rotational springs and dampers describing the viscoelastic effects at the joints of the body.

Furthermore, the dynamics of the muscle of the legs has been particularized by adding to the original model in [1] a mass-spring-damper system, which describes the motion of the muscles of the thighs. This system is constrained to a local reference placed on the femur link. The mass displacement is constrained to be perpendicular to the femur axis.

The overall kinematics, i.e. the body in a standing position and the subsystem associated to the thigh muscles, is depicted in Figure 1. This model comprises an additional translational degree-of-freedom in the fore-and-aft direction

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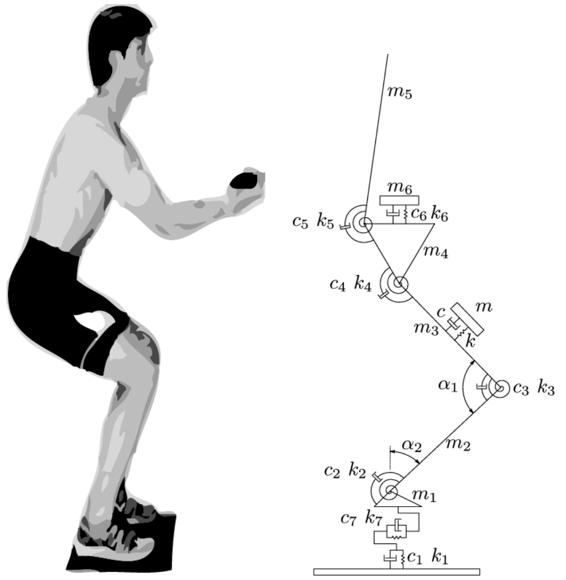

Figure 1 Kinematic scheme of the body in a standing position (with $\alpha_1 = 90°$ and $\alpha_2 \approx 46.3°$)

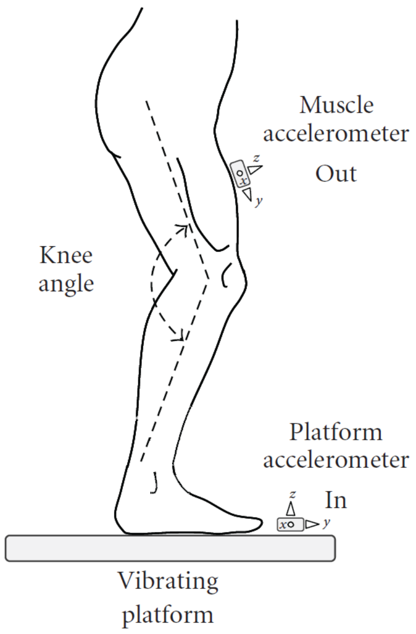

Figure 2 Scheme of the measurement setup.

at the feet, which represents some shear deformation occurring at the soft tissue of the feet.

The multi-body system associated to the kinematic scheme of Figure 1 is implemented and simulated in the modeling environment for 3-D mechanical systems provided with Matlab/SimMechanics. Figure 3 gives the block diagram representation in SimMechanics of the multi-body system under study.

The SimMechanics environment formulates and solves the equation of motion of a general multi-body system; therefore, it provides a modeling approach which is free from deriving the differential equations underlying the Newtonian dynamics of mechanical systems. A multi-body mechanical system can be represented using rigid blocks, joints blocks, constraint and force elements, elastic and viscous elements, which have a definite physical meaning when interconnected by signal lines within the SimMechanics scheme. Sensor blocks can also be used to measure the kinematic variables of the simulated mechanical system.

The values of the inertial and geometric properties of the musculoskeletal structure of Figure 1 and the parameters associated to the elastic and viscous elements, are drawn from [1], for a *knees more bent* postures. The SimMechanics blocks associated to the vibrating platform takes as inputs the measurements of displacement and velocity derived from experimental acceleration signals.

B. Experimental tests

The time-profiles necessary to the identification of the subsystem of the thigh muscles are obtained from WBVs experiments. The experimental protocol is similar to that adopted in [10] (see the experimental set-up of Figure 2). A vibrating platform (XP Multipower – TSEM S.p.A., Padova-Italy) has been actuated to generate vertical displacements with a peak-to-peak amplitude of about 1.2 mm. The platform displacement has been modulated through a linear frequency sweep profile which, in an ascending phase, ranges from about 15 to 66 Hz and, in the descending phase, decreases from 66 to 15Hz. Frequency sweep time interval of each phase has been set to 26 seconds, corresponding to an increase rate of about 2 Hz per second.

A male subject (age 21 years, height 173 cm, weight 70 kg athletically untrained), not affected by any known neurological or musculoskeletal disorder, were requested to hold hack squat position during vibration exercise. In the hack squat posture, subjects bent their legs at the knees with the angles reported in Figure 1.

Accelerometer signals at the vibrating platform level and on the thigh have been acquired from tiny and lightweight (less than 10 g) tri-axial MEMS, accelerometers (Freescale Semiconductors). The accelerometers were placed at 50% on the line from the anterior spina iliaca superior to the superior part of the patella for the Rectus Femoris (RF) muscle.

The signals were sampled at 2048Hz and logged to the PC via a multi-channel 16-bit data acquisition card (NIDAQ Card 6251)

C. Identification of the model parameters

The parameters of the subsystem describing the dynamics of the motion of the thigh muscles, i.e. the mass *m*, the stiffness parameter *k* and the damping coefficient *c*, have been optimized through the Simulink Design Optimization of Matlab using a Nonlinear least squares optimization method by comparing the simulated response of the SimMechanics model with the experimental measurements acquired from

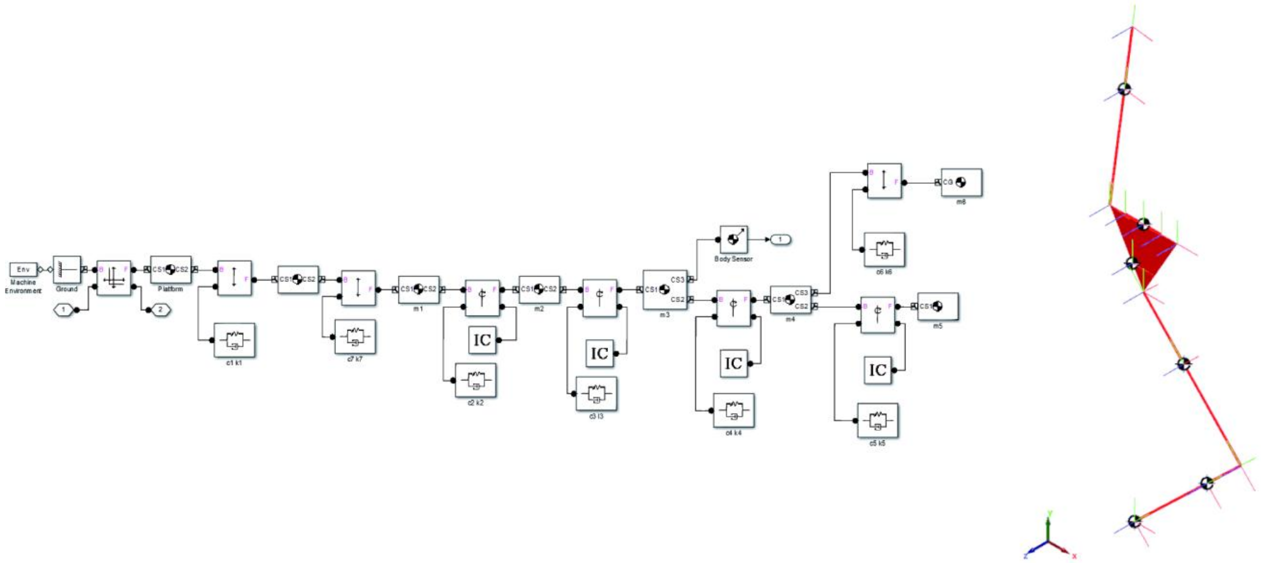

Figure 3 Block diagram representation in Matlab/SimMechanics of the multi-body system under study (left), and 3-D model representation (right).

the Z-axis readings of the accelerometer placed at RF muscle. The profiles of the displacement of the mass *m* can be readily obtained from simulations by placing a sensor block on the local reference at the femur link in the SimMechanics representation.

The optimization procedure for system identification minimizes the root mean squared error (RMSE) between model and experimental data. As result of the optimization, the procedure provides a local solution.

III. RESULTS

The parameter of the subsystem of the thigh muscles were identified over the ascending and the descending phases of the vibratory stimulus. The optimal set of parameters is reported in Table 1.

TABLE 1
OPTIMAL PARAMETERS OF THE SUBSYSTEM MODEL

Stiffness coefficient - k [N/m]	9.768×10^4
Damping coefficient - c [N s/m]	29.486
Mass - m [kg]	9.081

The identified parameters enable the SimMechanics model to adequately fit the experimental data during the descending phase, as shown in Figure 4.

Several sets of initial guesses have been assigned at the start of the optimization procedure in order to improve the goodness of fit.

For an initial guess m_0=18.5 [kg] k_0=1.6546×10^5 [N/m] c_0=905.832 [N s /m] the cost function converges to the optimal value in about 30 iterations, as Figure 5 shows.

To assess the plausibility of the model, some parameter sensitivity tests have been performed.

The effect of the variations of the identified parameter (mass *m*, stiffness *k* and damping coefficient *c*) on the RMSE between simulated and experimental data has been evaluated.

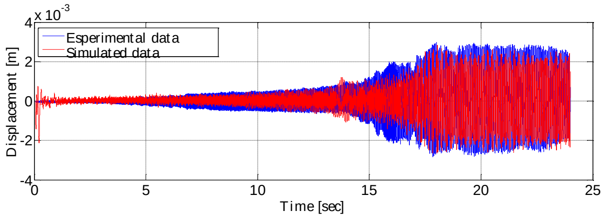

Figure 4 Comparison between simulated and experimental data of the displacement of the thigh.

Table 2 shows the percent change of RMSE with a +/-25% change of the identifies values of the model parameters, giving a measure of robust stability of the solution.

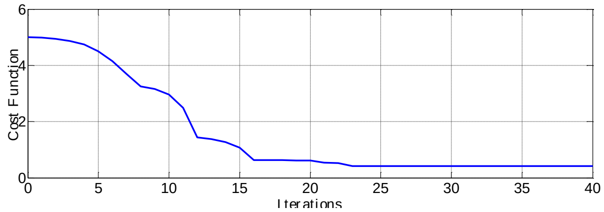

Figure 5 Trend of RMSE cost function during identification procedure.

TABLE 2
Result of sensitivity analysis – RMS % change

	-25 %	+25%
k	21.4246	51.2527
c	0.7356	0.2892
m	116.9903	16.5977

From the sensitivity analysis, it is clear that the model can reproduce some robustness properties typical of physiological systems.

It is noteworthy that a single set of parameters does not allow to achieve the same goodness of fit over both phases of the experiments. This can be confirmed by inspection of the experimental data from which an asymmetry of the vibratory response is evident. This behavior, which is inherent to the history of the vibration frequency, may depend both on some dynamical properties of the muscle tissue (e.g. hysteresis effects) and on individual characteristics of the subject, such as anatomical conformation, posture and stiffness of muscles.

IV. CONCLUSION

In this paper, a lumped parameter model, which is aimed to characterize the dynamics of the muscle motion of the legs in subjects during vertical whole body vibration treatments, has been developed starting from accelerometer experimental data. The multi-body mechanical system associated to the human musculoskeletal structure standing on a vibrating platform has been implemented and simulated in Matlab/SimMechanics.

The key parameters of the model have been identified through an optimization procedure which minimizes the RMSE between the simulated and experimental data.

The model with the identified parameters provides an adequate goodness of fit for the descending phase of the vibration stimulus which is frequency modulated.

The structure and the parameters of the model have been selected as one of the minimal configurations which recovers the main dynamic features of the vibration response of the muscle legs. The description of the behavior depending on the history of the vibration stimulus, i.e. some hysteresis effects in the vibration response, may require more complex dynamical models which nonlinear structure and additional parameters.

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