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Factoring Muscle Activation and Anisotropy in Modelling Hand-Transmitted Vibrations: A Preliminary Study †

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Abstract: Pushing and gripping forces may contribute to Hand-Arm Vibration Syndrome but, thus far, have not been taken into account in vibratory dose assessment according to the current standards. To obtain a better understanding of the symptom onset, we developed a finite element model of the hand to replicate its vibratory behaviour in gripping and pushing actions. In a case study, Supersonic Shear Imaging measurements revealed the significant dependence of muscle stiffness and anisotropy on gripping. The use of these measurements in our model showed that muscle activation influences the driving-point mechanical impedance of the hand and local vibration propagation.

Keywords: vibration hazard; elastography; muscle activation; transversally isotropic; modelling

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1. Introduction

In France, nearly 2.2 million workers are exposed to hand-transmitted vibration. Prolonged exposure to high-level vibration can lead to various disorders, known as Hand-Arm Vibration Syndrome [1]. In an attempt to reduce the health effects, the daily vibration dose received by workers is limited by law in Europe. However, dose assessment [2] has certain shortcomings. In particular, pushing and gripping forces exerted by the operator are not taken into account, although they significantly influence the hand's driving-point mechanical impedance (DPMI), which has been identified as a potential marker of vibration hazard [3]. To better understand the symptom onset, we investigated coupling force effects on vibration propagation in specific hand regions. Hence, we developed a finite element (FE) model for mimicking pushing and gripping actions to simulate their effects on the vibratory behaviour of the hand. The first step was to induce increased muscular stiffening stemming from muscle activation related to gripping. Supersonic Shear Imaging (SSI) was performed for local measurements of the shear elastic modulus in the hand muscles [4]. Thus, our approach consisted of measuring the stiffness of the first dorsal interosseous muscle (FDIM) of the hand as a function of gripping force. In addition, this technique allows for the measurement of the mechanical properties of muscles in directions parallel and perpendicular to their fibres. These measurements were then used to feed our FE model with muscle constitutive laws depending on both muscle activation and anisotropy. The aim of this paper is to demonstrate the feasibility of this approach in a case study and to quantify the influences of gripping-induced muscle disturbances on both DPMI and local vibratory transmissibility.

2. Materials and Methods

2.1. Measurement of Muscle Elasticity with Supersonic Shear Imagining

The shear elastic modulus was measured with an Aixplorer® ultrasonic scanner (Aix-en-Provence, France) in the SSI mode [4]. An experimental apparatus was set up to measure the shear elastic modulus of the FDIM of a volunteer gripping a handle instrumented with force sensors (Figure 1a). The probe was oriented beforehand using B-mode imaging either parallel or perpendicular to the orientation of the muscle fibres. The volunteer followed a given instruction by managing the grip level displayed on a screen. The protocol consisted of first measuring the maximum grip force solely to estimate the relative gripping forces. Next, the subject followed randomly chosen instructions for the application of gripping forces ranging from 0 to 30% with 5% increments. Both fibre directions were measured. The non-smoker volunteer was a 23-year-old male in good health. The shear elasticity modulus resulted in averaging data contained in a 5×5 mm^2 region-of-interest (ROI) extracted from raw elastography maps (Figure 2a,b).

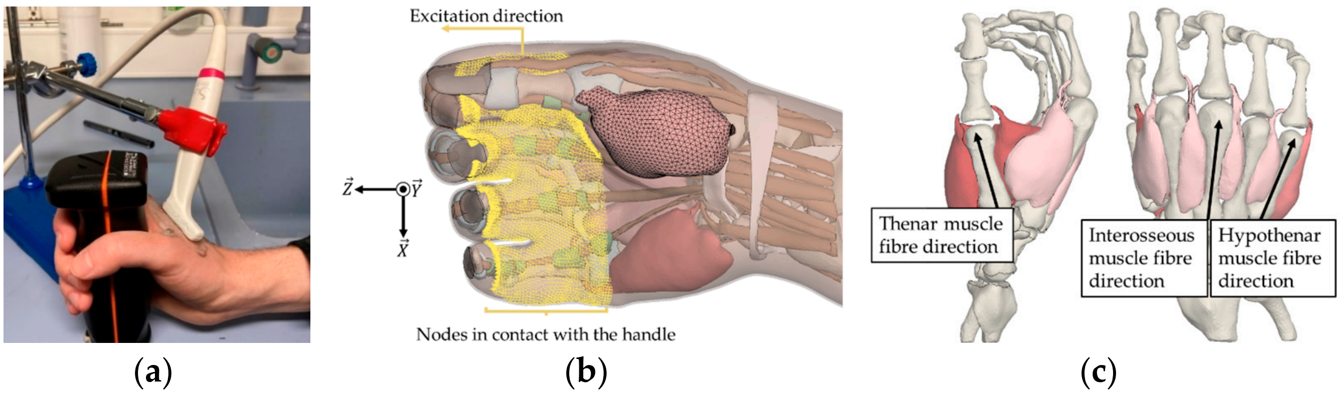


Figure 1. (**a**) Setup for measuring shear modulus with an ultrasonic probe while gripping an instrumented handle. (**b**) FE model of the hand. (**c**) Fibre direction for orthotropic constitutive laws.

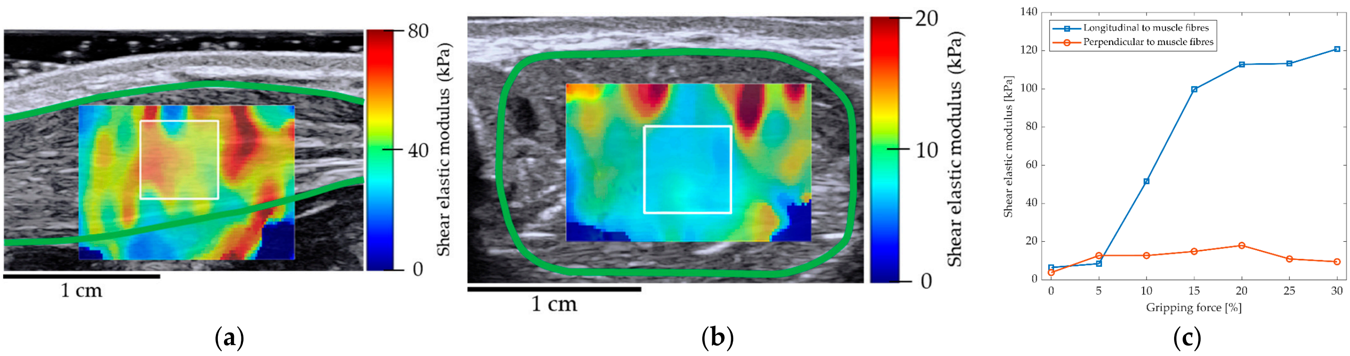


Figure 2. Examples of shear elastic modulus measurements obtained by SSI in the FDIM: (**a**) parallel and (**b**) perpendicular to fibres. The background represents the B-mode image with the muscle enclosed in green. The white square, which is 5 mm in length. indicates the ROI. (**c**) Average of longitudinal and perpendicular shear elastic moduli in the ROI as a function of gripping force.

2.2. FE Modelling of Hand-Transmitted Vibrations

Our FE hand model was built by segmenting MRI images of the hand of a 28-year-old male volunteer [5]. Most of the hand anatomical elements were included and meshed with tetrahedrons of around 1 mm (Figure 1b). The muscles were divided into three groups: interosseous, thenar and hypothenar. For each group, the muscle fibre direction matched the closest metacarpal bone direction (Figure 1c). The hand position corresponded to the grip on a handle without tightening. The initial stress and deformation fields were therefore taken to be zero. There were no boundary conditions placed on the wrist. The handle was excluded from the model, and the skin nodes in contact with it were fastened in all directions except for the direction of excitation (Figure 1b). The DPMI was calculated and compared to the standard ISO 10068 [6]. In addition, the vibratory transmissibility was computed in two areas: in the tissue under the median phalanx of the index (where an artery is likely to pass, not included in the model) and in the FDIM. Harmonic analyses were carried out by modal superposition over a range of 10–400 Hz. Modal damping was added to the system (from 17% to 2%, decreasing in frequency up to 200 Hz and remaining constant beyond). The calculations were performed using the FE software LS-Dyna® (Ansys, Canonsburg, PA, USA) by assuming linear elastic constitutive laws. The parameters were derived from [5], except those for the muscles, which were derived from elastography measurements. Three cases were computed: (i) isotropic elastic with no activation, where Young's modulus (E_L) was derived from the longitudinal elastic shear modulus (μ_L) measured at 0-5% gripping force (contact without tightening condition) and the longitudinal Poisson's ratio (υ_L) was derived from [7]; (ii) isotropic elastic with maximum activation, conducted in the same way as the previous case but at 30% gripping force; and (iii) transversally isotropic elastic with maximum activation, where the muscle behaviour was considered to be anisotropic, with rotational symmetry around the fibre axis. A shear modulus, Young's modulus, and Poisson's ratio were required for the longitudinal (μ_L, E_L, υ_L) and transverse (μ_T, E_T, υ_T) directions [7]. All the previous parameters stemmed from the shear elastic moduli measured at 30% gripping force, and the other parameters were deduced from [7].

3. Results

3.1. Effects of Gripping Force on Muscle Elasticity and Fibre Anisotropy

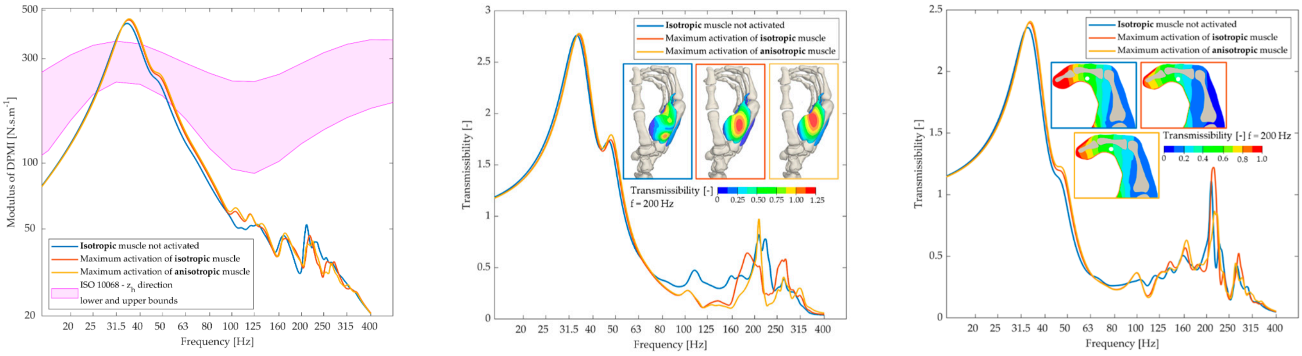
Elastography measurements highlighted that the shear elastic modulus of the FDIM evolved differently depending on the fibre orientation (Figure 2a,b). Parallel to the fibres, the shear modulus increased by more than 12 times between 0 and 30% strength, with a strong increase between 5 and 15% (Figure 2c). Perpendicular to the fibres, the modulus remained almost constant with the gripping force (Figure 2c). These measurements allowed us to identify the parameters of the FE model described in Table 1.

Table 1. Muscle properties used in the FE simulations.

	Isotropic Muscle		Anisotropic Muscle with Maximum Activation	
	No Activation	**Maximum Activation**	**Longitudinal**	**Transversal**
Shear elastic modulus	Not used	Not used	μ_L = 121.0 kPa	μ_T = 9.0 kPa
Young's modulus	E_L = 22.4 kPa	E_L = 338.8 kPa	E_L = 338.8 kPa	E_T = 25.2 kPa
Poisson's ratio	υ_L = 0.499	υ_L = 0.499	υ_L = 0.499	υ_T = 0.963

3.2. Effects of Muscle Activation on DPMI and Local Transmissibility

The resonance of the wrist around 35 Hz is observable in both the model and standard ISO 10068 DPMI. At higher frequencies, the model differs from the standard (Figure 3a). Muscle activation had a marked effect on the global DPMI and local transmissibility beyond 100 Hz, changing the amplitude and frequency of the peaks as well as the spatial nature of the harmonic response in the muscle (e.g., Figure 3b maps).



(**a**) (**b**) (**c**)

Figure 3. (**a**) DPMI of FE model compared to standard ISO 10068. (**b**) Averaged vibration transmissibility between the handle and the first dorsal interosseous muscle. (**c**) Vibration transmissibility between the handle and the tissue under the median phalanx of the index (white dot).

4. Discussion and Conclusions

The SSI technique demonstrated an ability to measure the mechanical elasticity of the FDIM. It revealed that the evolution of stiffness is strongly dependant on muscle activation and fibre orientation. Many sources of uncertainty arose during the measurements. For example, muscle heterogeneity (Figure 2a) and probe orientation, with regard to fibre direction, may be responsible for measurement discrepancies. Particular attention should be given to rendering the apparatus more robust before extending the measures to a cohort of subjects.

The model showed that muscle activation significantly affects the transmission of vibrations beyond 100 Hz. The gap between the DPMI computed by our model and that of ISO 10068 may be explained by the numerous simplifications made. More realistic boundary conditions should be applied to the wrist. In addition, modal superposition may only take into account basic viscoelastic effects. Hence, more complex rheological models will have to be used with direct resolution methods or by using our model in the time domain.

In conclusion, we succeeded in using the SSI technique to link active hand muscle elasticity with gripping force to feed a complex FE hand model. Our model allowed us to compute dynamic responses to vibrations and quantify the effect of local muscle activation on vibration propagation within the hand.

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Informed Consent Statement: Informed consent was obtained from all the subjects involved in the study.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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