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ON THE PHYSICAL FUNDAMENTALS OF HUMAN PERCEPTION AND MUSCLE DYNAMICS: FROM THE FULCRUM PRINCIPLE TO PHONONS

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Abstract. *The fulcrum principle establishes that a subthreshold excitatory signal (entering in one sense) that is synchronous with a facilitation signal (entering in the same or a different sense) can be increased (up to a resonant-like level) and then decreased by the energy and frequency content of the facilitating signal. As a result the sensation of the signal changes according with the excitatory signal strength. In this context, the sensitivity transitions represent the change from subthreshold activity to a firing activity in neurons. Initially the energy of their activity (supplied by the weak signals) is not enough to be detected but when the facilitating signal enters the brain, it generates a general activation among neurons, modifying their original activity. Here we will present several experimental examples on how it works and discuss a plausible model that would help us to understand some conditions such as autism. Moreover we will describe another model that uses the notion of phonons to correlate some known experimental muscle dynamics results, such as the muscle fibers electromyography power spectrum density shape and its shift due to temperature changes. In the former case a non-linear oscillator potential is used to raise a biestable state system where one state represents subtreshold activity of neurons and the second the suprathreshold condition. The latter case involves the use of linear oscillators with discrete frequency states.*

1 INTRODUCTION

Human perception is the bridge that links our sensations and consciousness with the real world. This bridge is built trough the multisensory integration process that our nervous system performs with all the signals generated by our senses. When we try to explore human perception we have to use Psychophysics. The theory of psychophysics was formulated in 1860 when the physicist and philosopher Gustav Theodor Fechner published Elemente der Psychophysik. He coined the term "psychophysics", describing "the analysis of perceptual processes by studying the effect on a subject's experience or behaviour of systematically varying the properties of a stimulus along one or more physical dimensions". This scientific methodology has contributed many crucial advances in determining perception and discrimination thresholds of our senses, performing the evaluation of its psychological representations as well [1]. A threshold is the point of intensity at which the participant can just detect the presence of, or difference in, a stimulus. Stimuli with intensities below the threshold are considered not detectable (hence: subthreshold). In addition to psychophysics, another important role was played by Electrical engineering. We know that communication systems [2] should have the purest signals (high Signal to Noise Ratio). One factor that conspires against any successful signal process is noise[2]. Noise is normally considered as a nuance and is not desired, but in some cases it may help to the system performance. For example, Stochastic Resonance (SR) [3]. This phenomenon could be interpreted as the benefit in making possible the detection of a specific signal, having an insufficient intensity to reach the detector threshold, when an appropriate amount of noise is added to that signal [4]. In some way, the stochastic power available, improves the signal performance when it is confronted to its detector threshold. We could refer to this as subthreshold detection. Our research has been focalised in improving the performance of human's functional loops and contribute to enhanced sensory abilities. This could be achieved by providing the subject with an appropriate amount of facilitating noise or deterministic signals [5], something we call the Fulcrum principle. The application of this principle could give rise to a wide spectrum of new research applications.

From the pioneering work done by Carey [6] it is known that oscillations of motor nerve endplates determine the pattern of radiated mechanical pressure waves through the muscular fibers, expressed as cross-striations; these waves are reflected from both fibers' ends. The superposition of incident and reflected waves form a complex stationary wave system in the transversal and perpendicular fibers' direction. Therefore the energy state of a muscle is reduced to a problem of finding the different possible types of standing waves. As the energy becomes greater the frequency increases and the wavelengths becomes shorter. With decrease of energy there is a corresponding decrease of wave frequency accompanied by longer wavelengths. Physicists have encountered a similar problem before. In 1912, Peter Debye produced a model for the heat capacity in solids, which turns out to be very accurate. In this model, the atoms in a solid are regarded as connected by springs. They vibrate in a tridimensional complicated way. Debye simplified the problem by treating the vibration as a superposition of waves of different frequencies where the frequency of each superposed wave is quantised. A quantum of this vibration energy is called a phonon. The thermodynamical properties of a solid are directly related to its phonon structure. In the case of striated-muscle anatomy we found a bundle of fibers and inside each fiber we encounter the myofibrils that are formed by a chain of contractile muscle units, the sarcomeres. Thus, we will propose that at thermal equilibrium the collective movement of the sarcomeres can be seen as phonons. In this work we present and show several examples of the Fulcrum principle and that the muscular electrical activity power spectral density in the gastrocnemius medial muscle may be described by Debye's theory for complex atomic vibrations in a solid.

2 THE FULCRUM PRINCIPLE

The fulcrum principle[7] establishes that a subthreshold excitatory signal (entering in one sense) that is synchronous with a facilitating signal (entering in a different sense) can be increased (up to a resonant-like level) and then decreased by the energy and frequency content of the facilitating signal. As a result, the sensation of the excitatory signal changes according to the facilitation signal strength. In this context, the sensitivity transitions represent the change from subthreshold activity to a firing activity in multisensory neurons. Initially the energy of their activity (supplied by the weak signals) is not enough to be detected but when the facilitating signal enters the brain, it generates a general activation among multisensory neurons, modifying their original activity. The result is an integrated activation that promotes sensitivity transitions and the signals are then perceived. In the following sections we will show several examples of this principle at work.

2.1 Excitatory: Tactile-Deterministic-Subthreshol; Facilitating: Auditory-Stochastic-Suprathreshold.

In [4, 5] we present a series of experiments where the effect of auditory noise on tactile sensations in human subjects was investigated. Tactile vibrations were delivered to the middle finger of the right hand of the subjects at a frequency of 100 Hz and were asked to report the tactile sensation. The results showed that as the noise level increased, the threshold decreased reaching a minimum and then increased in a typical stochastic resonance signature fashion. In general, the subject's minimum peaks were not always localized at a specific noise level but within a band centered at 69± 7 dBSPL. In a second experiment, sixteen subjects used two different auditory stimuli plus the baseline condition (no noise). One stimulus was a specific auditory noise condition, and another was a 3D-like sound. Both sounds had an intensity of 69 dBSPL and the 3D sound contained frequencies in a similar range as the auditory noise (between 100 Hz up to 19 kHz). The 3D sound gave the impression of very close movements near, up and down, and around the subjects' head. When comparing the 3D sound and baseline conditions. Eight subjects augmented significantly their thresholds comparatively to baseline condition, four subjects lessened theirs thresholds and in other four subjects the threshold values remained unchanged. In the case of the auditory noise and baseline condition. Twelve subjects significantly lessened their thresholds, only two subjects increased their thresholds and another two subjects had unchanged threshold values. In a different study Yasuda et al. [8] examined how the response probability of the tactile blink reflex varies with the intensity of auditory white noise. Tactile stimuli (signals) were given by an air puff at about 10 mm distance away from the lateral canthus. Tactile blink reflexes were detected by an electromyogram of the orbicularis oculi muscle with pairs of Ag/AgCl surface electrodes. Gaussian white noise was administered through headphones. The results revealed that the response probability of the tactile blink reflex at 70 dB of white noise was significantly higher than those at the other noise levels. Furthermore, when the auditory noise was replaced with 70 dB pure tone (1 kHz), the optimization of the response probability by 70 dB of white noise disappeared.

2.2 Excitatory: Visual – Deterministic- Subthreshold; Facilitating: Auditory Stochastic - Suprathreshold

In another series of experiments, we studied whether auditory noise can facilitate luminance-modulated (first order) stimuli detection in six subjects. Here the observers had to discriminate between vertical or horizontal luminance-modulated stimuli (LM) defined sinusoidal gratings [4]. As in our previous auditory-tactile experiments, the visual threshold profiles of the observers varied as a function of the different auditory noise levels demonstrating a typical stochastic resonance function with zones of threshold values significantly different from the baseline condition. The maximum sensitivity average peak (lowest average threshold) for our data was 75 ±3 dBSPL for LM stimuli. Previous reports show an average value of 70±2.5 dBSPL for visual flicker detection [9] and a value of 73.8±15.5 dBSPL for a luminance-defined stimulus [10]. Moreover, we studied whether auditory noise can facilitate contrast modulated (second order) stimuli detection. The observers had to discriminate between vertical or horizontal contrast-modulated stimuli (CM) defined sinusoidal gratings [4]. Again, the visual CM threshold profiles of the observers varied as a function of the different auditory noise levels demonstrating also the typical stocahstic resonance function. The average peak was found at 70±2 dBSPL for CM stimuli. Clearly the LM and CM peaks are inside the same experimental region and there is no significant difference between them meaning that, within the experimental accuracy we have used, both facilitation mechanisms are similar.

2.3 Excitatory: Proprioception – Deterministic- Subthreshold; Facilitating: Auditory - Stochastic - Suprathreshold

We evaluated electromyography activity (EMGA) responses of the subject's leg muscles during posture maintenance with different auditory noise conditions. The EMGA refers to the muscle's activity during posture maintenance. In this context a less stable posture represents more activity of the muscles related to this task. The subjects were asked to stand with their feet aligned one in front of the other and touching like in a tightrope position. The normalized power specral density of the EMGA (EMGA-PSD) was modulated by the noise showing the well known inverse curve shape signature in all the subjects and surprisingly, the subject's averaged peak was 74±4 dBSPL, which lies in the same experimental range found in our previous experiments. In another investigation it has been demonstrated that tactile stimulation of the foot with noise could increase postural stability by acting on the somatosensory system and that noise can induce transitions in human postural sway [11-13].

2.4 Excitatory: Motor – Deterministic- Subthreshold; Facilitating: Auditory - Stochastic - Suprathreshold

Fine-motor performance of the hand is more than important in our life and work. However, some injuries might damage the hand fine-motor performance. Previous studies show that fine-motor performance of the hand might be improved according to the mechanism of coactivation [14]. Lei Ai and colleagues tested whether fine-motor performance could be enhanced by the presence of auditory noise. They used a pegboard containing 50 holes arranged in four rows and 50 metal pins placed in a container. In every trial subjects were asked to pick these 50 pins with their right hand, one by one, from the container and insert them into 50 holes on the peg-board. Every hole was inserted by one pin. If one pin was dropped during the transfer, they were instructed to pick the next pin from the container to insert the hole that they just failed. The dependent variable was the length of time required for completing the process of inserting all the pins. The less the time the more dexterous the hand control. The result was a U-shape function of the intensity of different levels of auditory noise with the subjects' average peak at 68±1 dBSPL, showing that optimal auditory noise can largely improve the fine-motor performance.

2.5 Excitatory: Attention – Subthreshold; Facilitating: Auditory– Stochastic - Suprathreshold

Noise is typically conceived of as being detrimental to cognitive performance. However, a certain amount of noise can benefit performance. Soderlund et al. investigated cognitive performance in noisy environments in relation to a neurocomputational model of attention deficit hyperactivity disorder (ADHD) and dopamine [15]. They hypothesized that dopamine levels modulate how much noise is required for optimal cognitive performance. They experimentally examined how ADHD and control children responded to different encoding conditions, providing different levels of environmental stimulation. Participants carried out a high memory performance task and a low memory task. These tasks were done in the presence, or absence, of auditory white noise. They found that noise exerted a positive effect on cognitive performance for the ADHD group at 78 DBSPL and deteriorated performance for the control group at this same level. However the control group peaked at 70 dBSPL indicating that ADHD subjects need more noise than controls for optimal cognitive performance.

2.6 Excitatory: Imagery- Subthreshold; Facilitating: Auditory– Stochastic - Suprathreshold

Agnosia is usually associated with the bottom-up processing stream, inability to extract relevant information from the sensory data. It is commonly agreed that top-down processes help to establish conscious percepts [16]. Top-down connections in most brains are sufficiently strong to create activation needed to form a vivid percept, but what happens if they are too weak? This general condition may be called "imagery agnosia", as subjects may show all kinds of symptoms typical for agnosia when required to perform some tasks based on imagery. In [16] the researcher, who claimed having this agnosia condition, tested the conjecture that top-down activations due to imagery are simply too weak to establish brain states that could be uniquely categorized and lead to well defined percepts by using crosmodal stochastic resonance effects. He used auditory white noise at about 70 dB [28] trying to induce auditory or visual imagery in this way. He mentioned that the method seems to be promising, although the images and sounds were dim, unstable, struggling to establish themselves and falling after a few moments.

2.7 Excitatory: Visual – Deterministic - Subthreshold; Facilitating: Tactile – Stochastic - Suprathreshold

In another series of experiments, we applied different tactile noise intensity levels plus a baseline (no tactile noise) in different subjects [7]. We have measured absolute first order visual (in arbitrary units) thresholds and then normalized. The tactile noise was presented by means of a specific designed transferred signal spectrum actuator (TSSA) that converted the auditory signal spectrum energy into mechanical signal spectrum energy. The subjects held the TSSA against their right internal metacarpus. The tactile noise has a cut-off frequency around 1kHz. We found that tactile noise also facilitated first order stimuli perception similar to the auditory noise case.

2.8 Excitatory: Tactile – Deterministic- Subthreshold; Facilitating: Auditory - Deternistic - Suprathreshold

In this experiment [5], the auditory stimuli were presented binaurally by means of a pair of high-precision headphones. The electrical amplitude signal was set to a subtreshold level (1.5% below threshold) and the auditory signal had a fixed amplitude of 9 mV (peak voltage). The corresponding EMGA-PSD enhancements associated to tactile sensitivity ranged between 3% and 9% for all the subjects. In a second experiment, we tested tactile-auditory interaction using deterministic auditory signals with different amplitudes and measured the EMGA-PSD. A different amplitude of the auditory signal was tested at each session. The six amplitudes were 0, 8, 12, 20, 30, and 300 mV (peak voltage) at the amplifier exit. The results demonstrate that as we increased the amplitude of the auditory stimulus, the EMGA-PSD increased, reached a maximum, and then decreased (inverted- U-shaped function). This implies that there is indeed a particular intermediate level of auditory stimulation at which tactile auditory integration is optimally enhanced.

2.9 Excitatory: Tactile – Deterministic- Subthreshold; Facilitating: Visual - Deterministic- Suprathreshold

We also investigated [5] how tactile perception and the corresponding EMGA-PSD were affected when the amplitude of the tactile stimulus was subthreshold (1.5% below threshold) and a suprathreshold visual stimulus was presented concurrently. The biphasic visual signal was displayed on an oscilloscope and looked like a dot expanding to a line, first up and then down. The visual stimulus augmented tactile perception and the corresponding EMGA-PSD. The enhancement ranged from approximately 1.03 (increase of 3% relative to baseline) to 1.1 (increase of 10%).

2.10 Excitatory: Motor – Deterministic- Subthreshold; Facilitating: Motor - Stochastic-Suprathreshold

The consequences of spinal cord injury or Parkinson's disease are not just a break in communication between neurons; a cascade of events occur that promote further neuronal degeneration, cell death and motor dysfunctioning [17]. Locomotion training is a very effective tool in neuronal degeneration rehabilitation. Haas [17] has used vibratory stimulations, leading to reflex responses similar to reflex elicitations during human locomotion. He found that stochastic mechanical stimulations might be a useful method to counteract neuronal degeneration and to promote regenerative processes. His patients either stood up or sat down in a special chair and both legs were connected with two independently oscillating platforms. The platforms could oscillate with a mean frequency of 6 Hz and superimposed by random and stochastic influences which facilitate neuronal threshold crossing and enhance neuromuscular activity. Patients with Parkinson's disease and spinal-cord-injury patients that were stimulated regularly lead to significantly improved postural control and locomotion abilities. Interestingly, treated Parkinson's disease patients also showed reduced symptoms (tremor, rigidity) in the upper extremities. As improvements in manual coordination (for instance writing performance) were confirmed in further standardized experimental setting, it seemed unlikely that this vibratory stimulation affected only the muscle or exclusively the peripheral nervous system. That is, if only the lower limbs were excited, how could we explain improved writing performance?

3 MATHEMATICAL MODEL FOR THE FULCRUM

We can simulate neurons as natural devices with dynamics that consist of random low amplitude motions (subtreshold neuronal activity) from which escapes occur at certain intervals [18]. The escapes are referred to as firings, and are associated with high amplitude bursts (spikes). We begin by proposing a bistable model for the response of neurons as:

$$\ddot{x} = -V'(x) + \varepsilon\left[\gamma\, Cos(\omega_0 t) + \sigma G(t) - \beta \dot{x}\right]. \tag{1}$$

Where x represents the neurons' amplitude activity, $\dot{x}$ is how their activity changes with time), ε is a perturbation parameter that may have a stepwise variation over. $\sigma Cos(\omega_0 t)$ represents the excitatory weak signal, $G(t)$ is the facilitating signal and it can be a nearly white noise process or a deterministic one, γ , σ and β are adjustable parameters, *V*(*x*) is a double-well potential defined by a polynomial given by :

$$V(x)=\left\{\begin{matrix} \alpha^{-}\left(-\dfrac{x^{2}}{2}+\dfrac{x^{4}}{4}\right) & x\le 0 \\ \alpha^{+}\left(-\dfrac{x^{2}}{2}+\dfrac{x^{4}}{4}\right) & x>0 \end{matrix}\right\}. \tag{2}$$

To achieve good neuronal time history simulations, the potential *V*(*x*) must be asymmetric, which is deeper for $x > 0$ than for $x \le 0$. The quantities between brackets in Eq. (1) represent excitatory, facilitating energy, and energy losses. Eq. (1) can achieve simulations of neuronal time histories (with the appropriate parameter values) and it has solution with the qualitative features observed in the experiments described earlier.

3.1 Fulcrum neuron firing condition

It is possible to show that the necessary condition for the Fulcrum to occur [4], for the stochastic process $G(t)$, is

$$\left(-4\beta\sqrt{\alpha^{-}}/3\right)+\gamma S(\omega_{0})+\sigma\sum_{k=1}^{N}a_{k}S\left(\omega_{k}\right)>0, \tag{3}$$

where the constants a_k are related to the Fourier one-side spectral density. For a second harmonic signal $\sigma Cos(\omega_1 t)$ instead of white noise the conditions writes:

$$\left(-4\beta\sqrt{\alpha^{-}}/3\right)+\gamma S(\omega_{0})+\sigma S\left(\omega_{1}\right)>0, \tag{4}$$

where, $S\left(\omega_j\right)=\left(2/\alpha^{-}\right)^{1/2}\pi\omega_j \sec h\left\{\pi\omega_j/(2\sqrt{\alpha^{-}})\right\}$ is known as the Melnikov scale factor. It is clear that if we want to optimize the energy transfer from the stochastic process *G*(*t*) or deterministic process $\sigma Cos(\omega_1 t)$ then the spectral density of *G*(*t*) needs to contain frequencies around the Melnikov scale factor maximum and the frequency ω_1 from the signal $\sigma Cos(\omega_1 t)$ must be centered at the Melnikov scale factor $S(\omega)$ peak as well. By using Eqs. (1-4) we have shown that for low noise intensities the energy transfer from the noise to the signal is not enough to achieve the synchronization and as a result the subtreshold activity dominates and no firings occur. However as the noise intensity increases firings also increase up to a maximum peak, where the mean escape rate approximately equals the signal frequency. Beyond this point, random firings can occur at different frequencies meaning that the synchronized energy transfer from the noise to the signal is destroyed and the signal is embedded in the subtreshold activity. It is clear from Eqs. (3-4) that if we increase the energy losses we have to increase accordingly the excitatory energy to always fulfill the fulcrum neuron firing condition. This means that the energy transfer is always fixed no matter how long the neuronal network is.

3.2 Autism and the Fulcrum principle

The fifth consequence is related to a better understanding of disorders such as autism, in which altered sensory processing often occurs that causes perceptual dysfunction, it causes problems with one or more sensory channels from the world to the brain. In a very general

classification given in [19] the sensory channels are abnormal in one of the followings ways: Hyper: the sensory channel is too open and, as a result, too much stimulation gets in for the brain to be handled comfortably. Hypo: the sensory channel is not open enough and, as a result, too little of the stimulation gets in and the brain is deprived. White noise: the sensory channel creates its own stimulus because of faulty operation and, as a result, the message from the outside world is garbled or, in extreme cases, is overcome by the noise in the system. The broad autism classification can be qualitatively understood by using the neuron firing condition:
Let us assume in this case that the stochastic energy is due to the internal noise and the excitatory signal is deterministic. Therefore the Hyper type can be described by: small values of parameters β and α^{-} that make the energy losses small. This represents an internal noise energy level close to the energy losses level and a Melnikov scale factor that is very narrow (this is because α is small). With these conditions a very weak excitatory signal elicits neuronal firings and because of the Melnikov narrowness factor, the optimal condition for the firings is easily achieved (but only for a small frequency bandwidth). Note that if the frequency content of the excitatory signal is outside of this bandwidth then the classification will change to Hypo. Hypo condition: High values of parameters β and α^{-} that make the energy losses high. Therefore, the internal noise energy is lower than the energy losses. This represents a Melnikov scale factor that is very broad (this is because α^{-} is high). With these conditions a very strong excitatory signal is needed to elicit neuronal firing and, because the Melnikov factor broadens, more frequencies can induce the optimal condition for the firings with less selectively than the Hyper type. White noise condition: the stochastic energy is higher than both the energy losses and the excitatory signal combined. Then neuronal firings occur but they are mainly driven by the internal stochastic process. Note that nothing precludes that sensory channels present one or more classifications. That is, a person might be hyper or hypo for the different stimuli because optimal neuron firings depend on the frequency and energy content of the involved signals.

In the precedent sections we have seen that a model of a non-linear oscillator can help us understand the fulcrum principle in human perception. Nonetheless, there is another situation where the use of oscillators are very useful to explain neuron dynamics. For instance the muscular electrical activity power spectral density in the gastrocnemius medial muscle may be described by the complex movement of linear oscillators at thermal equilibrum. This will be discussed in the next sections.

4 PHONON-LIKE POWER SPECTRAL DENSITIES INDUCED ON HUMAN CALFS DURING ISOMETRIC CONTRACTIONS

4.1 Experiments

We asked two subjects to execute isometric contractions of their right gastrocnemius medial, 10% of the maximum voluntary contractions (MVC), while sitting confortability with eyes open. A single differential EMGA electrode was placed at the middle of the muscle right of all participants away from the innervations zones that for gastrocnemius muscles are located either at the perimeter of the muscle or at one end of the muscle [20, 21]. EMGA was tracked for 10 trials each lasting 10 second (one-minute pause between trials) with a Bagnoli (DELSyS, Inc.) handheld EMGA system. The EMGA-PSD was calculated by means of a FFT algorithm for each trial and then averaged for each subject. All the averaged PSDs were then fitted by means of equation:

$$P_{\nu,\nu_0} = A_p\left(\frac{\nu^3}{e^{\frac{\nu}{\nu_0}} - 1}\right), \tag{5}$$

where A_p and ν_0 are two fitting parameters. For the fitting we have use the non-linear least squares method implemented in matlab's curve-fitting tool. The study received ethical approval from the Institutional Review Board of the University of Montreal, Quebec, Canada.

4.2 Theory

Inside the muscles we find the fibers and they are supplied by terminal branches of one nerve fiber or axon whose cell body is in the anterior horn of the spinal grey matter (motorneuron). This nerve cell body with the long axon running down the motor nerve and its terminal branches constitute a motor unit (MU). The termination of the axon of the muscle fiber defines an area known as the endplate. These endplates are usually, but not always, located near the middle of the muscle fibers. An action potential descending the motoneuron activates almost simultaneously all the fibers of a MU and its known as a motor unit action potential [22]. When postsynaptic membrane of a muscle is depolarized, the depolarization propagates in both directions along the fiber. The membrane depolarization, accompanied by a movement of ions, generates an electromagnetic field in the vicinity of the muscle fibers, whose time excursion can be measured and the radiated power spectral density can be obtained. Let us assume that each muscle fiber can be treated as a vibrating string with energy associated to each standing wave or oscillation mode given by $E_n = n\pi^2 v_f A^2 \mu\nu$, where n is the harmonic index, v_f is the wave propagation velocity, A is the oscillation amplitude, μ is the linear mass density and ν is the frequency. If we assume that in average v_f, A and μ are constants then the energy is $E_n = nL\nu$ and $L = \pi^2 v_f A^2 \mu$. These modes can be observed in some experiments. For instance, Monster and Chan[23] studied a homonymous motorneuron pool that was volitionally activated during gradually changing isometric contraction of the extensor digitorum communis muscle. They showed the MUs' firing frequency behavior of 60 MUs with the force and clearly each MU presented a discrete set of frequencies instead of a continum of frequencies. Now, assuming that a person is at thermal steady state, that is within the thermoneutral zone between 20 and 30° C where the metabolic rate is almost constant [24]. Under these conditions these modes are in thermal equilibrum inside the muscle of volume V similarly to phonons. In that case, the average energy per mode is given by $\langle E\rangle = L\nu \big/ e^{\frac{\nu}{\nu_0}} - 1$, where ν_0 is a frequency parameter given by $\nu_0 = E_T/L$, where E_T is the thermal energy. The amount of modes per unit frequency contained in a volume V is $12V\pi\nu^2 \big/ v_f^3$, where we have assumed that are three different polarizations for the waves, two transversals and one longitudinal. Therefore, the energy spectral density in a volume V can be written as:

$$E_{\nu,\nu_0} = \frac{12V\pi L\nu^3}{v_f^3\left[e^{\frac{\nu}{\nu_0}} - 1\right]}, \tag{6}$$

If the spectral energy E_{ν,ν_0} is emitted by the fibrons then the power spectral density (PSD) radiated by a surface of area S, P_{ν,ν_0}, can be calculated by multiplying $E_{\nu,V}$ by $v_f/4$ [25], therefore $P_{\nu,S}$ is given by:

$$P_{\nu,\nu_0} = \frac{3S\pi L}{v_f^2}\left(\frac{\nu^3}{e^{\frac{\nu}{\nu_0}}-1}\right), \tag{7}$$

Which is identical to Eq. (5) with $A_p = 3S\pi L/v_f^2$.

4.3 Results

Figure 1 shows the fit results for the participants including the fit parameters. We can estimate the value of L by using experimental values for $v_f = 4 \ m/s$ [22, 26, 27], for A we take the value for the maximum stretch distance for sarcomeres' crossbridges as in [28] that is $30nm$. The linear mass density can be obtained indirectly by $\mu = \rho_V V/l_f$. For the volumetric mass density ρ_V we use the density of mammalian skeletal muscle value of $1060 \ Kg/m^3$ [29], for V the gastrocnemius medial volume value of $303.2 \pm 65.1 \ cm^3$ and the fiber length l_f equals $6.3 \pm 1.2 \ cm$ [30]. The L value we obtained is $1.8046x10^{-13} \pm 0.7383x10^{-13}$ Js. Where the final error is due to the propagation of the individual errors on V and l_f. This value agrees well with the value of $1.9017x10^{-13} \pm 0.8513x10^{-13}$ Js obtained in another study [31].

It is known that by decreasing the intramuscular temperature, the median frequency of the EMGA-PSD in a muscle shifts towards lower frequencies [32]. Since the the median frequency of Eq. (7) is given by $\nu_{med} = 3.503\nu_0$ and ν_0 is proportional to the thermal energy, therefore by decreasing the temperature the thermal energy, ν_0 and ν_{med} decreases consequently. Merletti and colleagues [32] cooled down the first dorsal interosseous muscle of human subjects from 33 ^{0}C to 15 ^{0}C. Subjects were asked to perform isometric constant-force abduction contractions of the index finger at 20% and 80% MVC levels. The initial median frequency $I\nu_{med}$ of the EMGA-PSD was taken as a reference (measured at 33 ^{0}C) and conform that the temperature decreased. Each calculated ν_{med} was normalized by $I\nu_{med}$ and multiplied by 100 to obtain the percentage initial median frequency $\%I\nu_{med}$. The relationship of $\%I\nu_{med}$ versus temperature was a linear relationship with a sensitivity (slope) of 3.03 %/^{0}C and 3.48 %/^{0}C for 20% and 80% respectively during maximal voluntary contraction. By using the same procedure we theoretically found that $\%I\nu_{med} = 100T_M/T_{M0}$, where T_M is the muscle's tempertaure, and for a temperature of 33 ^{0}C we obtained a sensitivity of 3.03 %/^{0}C. In a similar study[33] Petrofsky and Lind used the forearm muscles. Brief (3s) isometric contractions were exerted at tensions ranging between 10 and 100% of each subject's maximum strength. The temperature of the muscles during those contractions was varied by placing the forearms of the subjects in a controlled temperature water bath at temperatures of 10, 20, 30, and 40 degrees Celsius. The results of these experiments showed that the median frequency of the EMGA-PSD was directly proportional to the temperature of the exercising muscles during brief isometric contractions. For instance, for 10% MVC the slope was 4.771 ± 0.200 Hz/^{0}C.

Theoretically we know that $\nu_{med} = 3.503\nu_0$ and from [31] that $\nu_0 = 1.189T_M$, therefore the theoretical slope is 4.165 Hz/^{0}C.

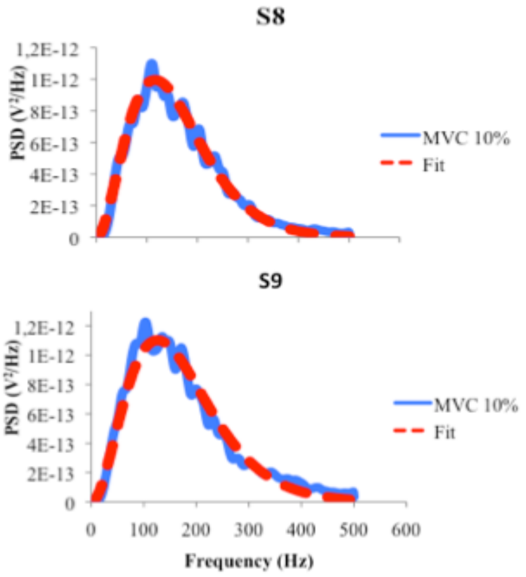

Figure 1: Maximum voluntary contraction of 10% in the right gastrocnemius medial for two subjects. S8 parameters: Ap=1.00764x10^{-17}, ν_0=41.12 Hz, S9 parameters: Ap=8.90136x10^{-18}, ν_0=44.31 Hz

5 CONCLUSIONS

- We presented the Fulcrum principle and give 15 experimental examples. The fulcrum can be modeled as an asymetric, anharmonic oscillator.
- This principle can help us to better understand how human perception ocurrs and comprehend human conditions such as agnosia, synesthesia and autism.
- We have shown that the EMGA-PSDs of isometric contractions in muscles can be described by Debye's theory of phonons or mechanical oscillation modes. We compared this model against experimental results concerned the temperature changes and the associated linear change of the EMGA-PSD median frequency. The model fits the theory well.

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