Asociación Argentina
de Mecánica Computacional

Mecánica Computacional Vol XXXVI, págs. 1815-1823 (artículo completo)
José G. Etse, Bibiana M. Luccioni, Martín A. Pucheta, Mario A. Storti (Eds.)
San Miguel de Tucumán, 6-9 Noviembre 2018

COMPUTATIONAL AND NUMERICAL SIMULATION OF THE BIOMECHANICS OF THE RAT'S VIBRISSA. PRELIMINARY STUDY OF THE INTERACTION WITH SURFACE MICROSTRUCTURES

Facundo A. Lucianna[a] **and Sonia M. Vrech**[b]

[a]*Laboratorio de Medios e Interfases (LAMEIN), Instituto Superior de Investigaciones Biológicas (INSIBIO), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Universidad Nacional de Tucumán (UNT), Avda. Independencia 1800, San Miguel de Tucumán, Tucumán, Argentina, flucianna@fbqf.unt.edu.ar, http://www.lamein.org*

[b]*Centro de Métodos Numéricos y Computacionales en Ingeniería, Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Universidad Nacional de Tucumán (UNT), Avda. Independencia 1800, San Miguel de Tucumán, Tucumán, Argentina, svrech@herrera.unt.edu.ar, cemnci@herrera.unt.edu.ar*

Keywords: Vibrissal System, Rat, Finite Element Method, Texture Discrimination.

Abstract. Vibrissae are specialized hairs located on the snout of several mammals, particularly in rats, commonly involved in tactile sensation. They allow the exploration and recognition of the surroundings through periodical forward and backward movements. The mechanical events evocated by contact are transmitted to the vibrissal follicle located at the whisker base, where they are transduced into electrophysiological signals that go from the afferent neurons to the primary somatosensory cortex. Spatial orientation, object localization and texture discrimination are some of the tasks that rats can do with this sophisticated system. Particularly in the latter case, the rat can discriminate between textures with a difference of 30 µm in roughness. This excellent capacity makes the vibrissal system an interesting subject of study for biological studies, as well as for its possible engineering applications. This work presents a two-dimensional computational model through a Finite Element formulation for the analysis of the mechanical behavior of the vibrissae in contact with surfaces of variable roughness. In order to do this, the study was restricted to the analysis of discrete events in the whisker kinematics resulting from its collision with surface microstructures. We analyzed a possible correspondence between the results obtained in terms of stress, and acceleration with the neural activity from electrophysiological studies in the literature. This work is a preliminary study in the development of a more complex and general numerical model that will allow the study of the correlation between the mechanical behavior with the neural activity of the vibrissal system.

1 INTRODUCTION

The vibrissal sensory system is present in many mammals but it is especially developed in rodents and particularly in rats (Prescott et al., 2009). Rats depend on the sensory input from their whiskers as primates depend on visual input (Krubitzer et al., 2011). Spatial orientation, localization, food discrimination and even social behavior such as courting or fighting, are some of the tasks that rats can do with this sophisticated system (Carvell and Simons, 1990). Many scientists from biology, bioengineering, biomechanics and mathematics have focused their attention on trying to understand the way this sensorial system works, for different purposes. Some teams have studied internal processes by analyzing the whisker, the follicle, the mystacial pad and the neuronal circuits. Scientists close to bioengineering have directed their attention to the development of biomimetic devices. They use this system to run applications such as object detection in robotics, enhancement of human haptic sensory systems, just to name a few.

The mechanical signals are generated from the body of the whisker to the follicle. These signals will be later transduced by mechanoreceptors. The rat actively moves the whisker, which is deformed elastically by interactions with the environment. It gets stuck and released with a complex inertial behavior which includes velocity and acceleration profiles and rotation about different axes. In addition, the follicle is oblong and has different and varied structures and mechanoreceptors at different levels (Kim et al., 2011). The shape of the follicle suggests that more than one mechanical variable of the whisker is codified by the vibrissal system per each vibrissa (Mitchinson et al., 2004).

1.1 The input of the vibrissal system

The sensor of the vibrissal system is the vibrissa and its follicle complex. Each whisker-follicle complex is where the information about the surroundings is transduced. They are arranged in a specialized facial structure at the snout, called the mystacial pad (Fig. 1a) (Albarracín et al., 2006). The rat moves the mistacial pad in a characteristic movement (whisking) as part of the rat's "sniffing behavior" (Prescott et al., 2009). The whiskers are often actively swept back and forth at high speeds (5 to 25 times/s) (Prescott et al., 2009). The animal coordinates head, nose and vibrissae movements and uses this exploratory behavior to gather information about object features in the environment such as location, shape, texture and size (Albarracín et al., 2006).

The whisker's shape is practically a linear truncated cone with a tapered tip and a circular cross section with a hollow medulla near the base (Quist et al., 2011). In adult rats, the typical length varies approximately from 10 mm to 50 mm (Quist et al., 2011) and depends on the location in the mystacial pad; the shortest are localized at the rostral part of the snout. Diameters range between 10 μm and 50 μm at the base of the whisker and about 5 μm at the tip (Prescott et al., 2009). The whisker has an inhomogeneous structure that produces different levels of elasticity in different sections, as reflected in Young's modulus. In a longitudinal analysis of the whisker, the average modulus is approximately 4 GPa at the base section and approximately 3 GPa at the tip (Quist et al., 2011).

Each vibrissa is anchored in a complex structure called the follicle–sinus complex (FSC) (Kim et al., 2011). The follicle is surrounded by a blood sinus and an outer collagenous capsule (Kim et al., 2011). The FSC is embraced by the vibrissal capsular muscle, which originates on the facial muscles, thereby enabling voluntary movement (Kim et al., 2011). The whisker movement exerts pressure both in the blood sinus and in the multilayers of tissue, producing the activation of the different mechanoreceptors distributed around the follicle (Ebara et al., 2002).

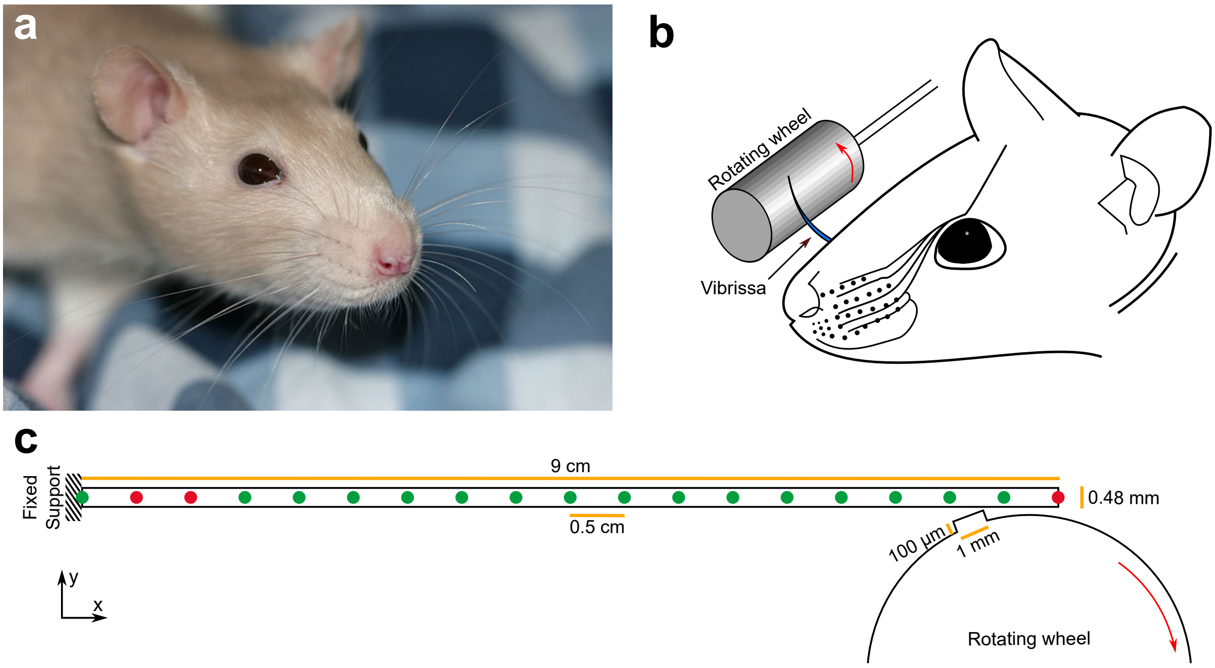

Figure 1: a - A pet rat showing the grid-like arrangement of the vibrissae (Photo by Dawn Huczek. CC-BY 2.0 License). b - Diagram of the electrophysiological experiment. c - The situation to be modeled. It shows the pseudo-vibrissa and rotating wheel dimensions (not in scale). The green and red circles are the representation of the 19 probe nodes. The red ones are the probe nodes used to measure the acceleration in the y-direction.

All these physical properties of the FSC and other related ones, like resonance and damping, will be among the critical determinants of the signals generated when a whisker contacts a surface (Prescott et al., 2009).

1.2 Texture perception

Between the different tasks that the rat can do with its whiskers, the one that we are going to focus on is texture perception. It was observed in different behavior experiments that the rat can identify roughness in the order of 100 μm, and a difference of 30 μm between two surfaces of similar characteristics (e.g. sandpaper) (Schwarz, 2016).

Nowadays, there is not a valid hypothesis that could explain how the mechanical interaction is transduced between the whisker and the surface, or more important, what is mechanically happening between the whisker and the surface (Schwarz, 2016). The most accepted hypothesis is called the *slip–stick* theory, also known as the *kinetic signature* theory (Diamond and Arabzadeh, 2013). It states that the trajectory of the whisker on a surface is characterized by an irregular skipping motion made up of intermixed low and high velocities, called *stick-slip events* (Diamond and Arabzadeh, 2013). Discrimination occurs because each texture is associated with a distinct trajectory of sticks and slips and the coarser the texture, the greater the rate or magnitude of slip-stick events (Diamond and Arabzadeh, 2013).

1.3 The interaction between the whisker and the surface microstructures

What happens between the whisker and surface is in the realm of speculation. We know that there are discrete high dynamics inertial events that are related to the texture, but we do not know exactly how they are and how is the relationship between them and the surface microstructures. Mainly because it is very difficult to capture the motion of the interaction between the whisker and the surface. In this regard, a good way to analyze that without all the difficulty of the motion capture, is applying a computational model.

We used as base an electrophysiological experiment that our research group did in the past (Fig. 1b) (Pizá, 2018). In that experiment, we used different sandpapers mounted on a rotating wheel. The rough texture covered the outer circumference of the wheel. Then, we used anesthetized rats with their heads fixed. We removed all whiskers but one from the mistacial pad, the vibrissa was so positioned that it rested against the rotating wheel at ~5 mm from its tip, along the plane of the surface, with the vibrissa tip pointing in the direction of the surface motion. An array of electrodes was inserted into the surface of the infraorbital nerve; therefore, we recorded the neural activity of that nerve. By means of signal processing, we found a correlation between the spike number at afferent level and the size of sandpaper grain. The coarser the sandpaper, the higher the neural spike count. A similar result was observed in the cortex in Lottem and Azouz (2008). We hypothesized the spike count is related to the slip-stick events that appear when the whisker collides with the different grains.

But in those experiments, we did not have any way of capturing the mechanical interaction between the whisker and the grains. In this work, we propose to analyze what happens using a computational simulation of the experiment and compare it with a physical experiment.

1.4 The physical experiment

We did an experiment similar to the electrophysiological experiment, but in this case, we used a pseudo-whisker (a piano string) (Lucianna, 2018). The base was fixed and the free end (the tip) was in contact with sandpapers mounted on a rotating wheel. The mechanical activity was recorded using an accelerometer at 1 cm of the base. The whole experiment, specially the size of the pseudo-vibrissa, was a scaled version of the original experiment.

1.5 The computational experiment

The same experiment was modeled using a 2-D Finite Element (FE) formulation, modeling the whisker collision with a single grain of the texture. In this FE analysis, we identified a good candidate of a slip-stick event and the key parts of the dynamic interaction (in terms of stress and acceleration) that could be used as trigger of a spike by the mechanoreceptors in the follicle. Also, we found a similar acceleration signal behavior from the physical experiment.

It is important to note that this work is a first step in the development of a more complex and general model that will allow the study of the correlation between the mechanical behavior with the neural activity of the vibrissal system.

2 MATERIALS AND METHODS

2.1 The situation to be modeled

A simplified simulation of the physical experiment, explained in the sub-section 1.4, was made. In this regard, we used all the geometrical values in the simulation obtained from Lucianna (2018). The analysis was restricted to a 2-D geometry (Fig. 1c). The pseudo-whisker was modeled as a rectangle of 9 cm of length and 0.48 mm of height correspondent to the cross section of the string used in the physical experiment. The material of the string was steel with 7.896 mg/mm^3 density and a Young's modulus of 82 GPa (Murphy, 1994). The rotating wheel was modeled as a perfect circle of 6 cm in diameter with a little square protuberance (the sandpaper grain) with a height of 100 µm and a length of 1 mm (Fig. 1c). The wheel rotated in the anticlockwise direction and at a constant angular velocity of 2.45 rad/s (Fig. 1c).

The modeled situation, of about 200 ms, consisted in the scenario where the pseudo-whisker contacts the grain and then releases it. The pseudo-whisker deformation was restricted to be elastic.

2.2 Software

The simulation was processed using ANSYS Workbench v15.0 as FE analysis software, while the post-processing analysis was done in Matlab 2018a.

2.2.1 Explicit FEM analysis

The study performed in this work focused on the evolution in time of the pseudo-whisker when it collided with the grain in a short amount of time (milliseconds). ANSYS Workbench offers an analysis system for this kind of situations by means of explicit dynamics analysis.

The basic equations solved by this type of analysis express the conservation of mass, momentum and energy in Lagrange coordinates. These, together with the material properties and a set of initial and boundary conditions, define the complete solution of the problem. For each time step, the equations are solved explicitly for each element, based on input values at the end of the previous time step. Only mass and momentum conservation are enforced. Energy conservation is constantly monitored for feedback on the quality of the solution.

The time integration used for this simulation was the Leapfrog method (Iserles, 1996). We used 50-time steps.

2.2.2 Initial conditions and boundaries

We used a fixed support at the base of the pseudo-whisker. All the contacts were frictionless.

As initial condition, the rotating wheel has a constant angular velocity of 2.45 rad/s in the anticlockwise direction (Fig. 1c).

2.2.3 Mesh

The pseudo-whisker was meshed with 900 uniform quadrilateral shell Belytschko-Tsay elements (Fish and Belytschko, 2007) (Fig. 2a). The rotating wheel was modeled as a rigid body with around 100 quadrilateral elements, with a refinement in the grain area (Fig. 2a).

2.2.4 Post-processing

The solution was obtained in terms of the equivalent stress (Von-Mises) and the acceleration in the y-direction, both as functions of time. The equivalent stress is a scalar proportional to the distortion elastic deformation energy (De la Rama and Mendoza, 1996). Also, we chose the acceleration in the y-direction to compare it with the results obtained in the physical experiment.

For the equivalent stress, the analysis was restricted to only 19 nodes at medium height of the pseudo-whisker, with a separation of 0.5 cm long between each one from the base to the tip. We called them *probe nodes* (Fig. 1c). For the acceleration, 3 probe nodes were considered, one in the end closer to the rotating wheel (the tip), and the other two at 0.5 cm and 1 cm of distance to the base (Fig. 1c), because that is the portion of the pseudo-whisker where the accelerometer was placed in the physical experiment (Lucianna, 2018), and also, it is where the mechanoreceptors are placed in the real whisker-follicle complex.

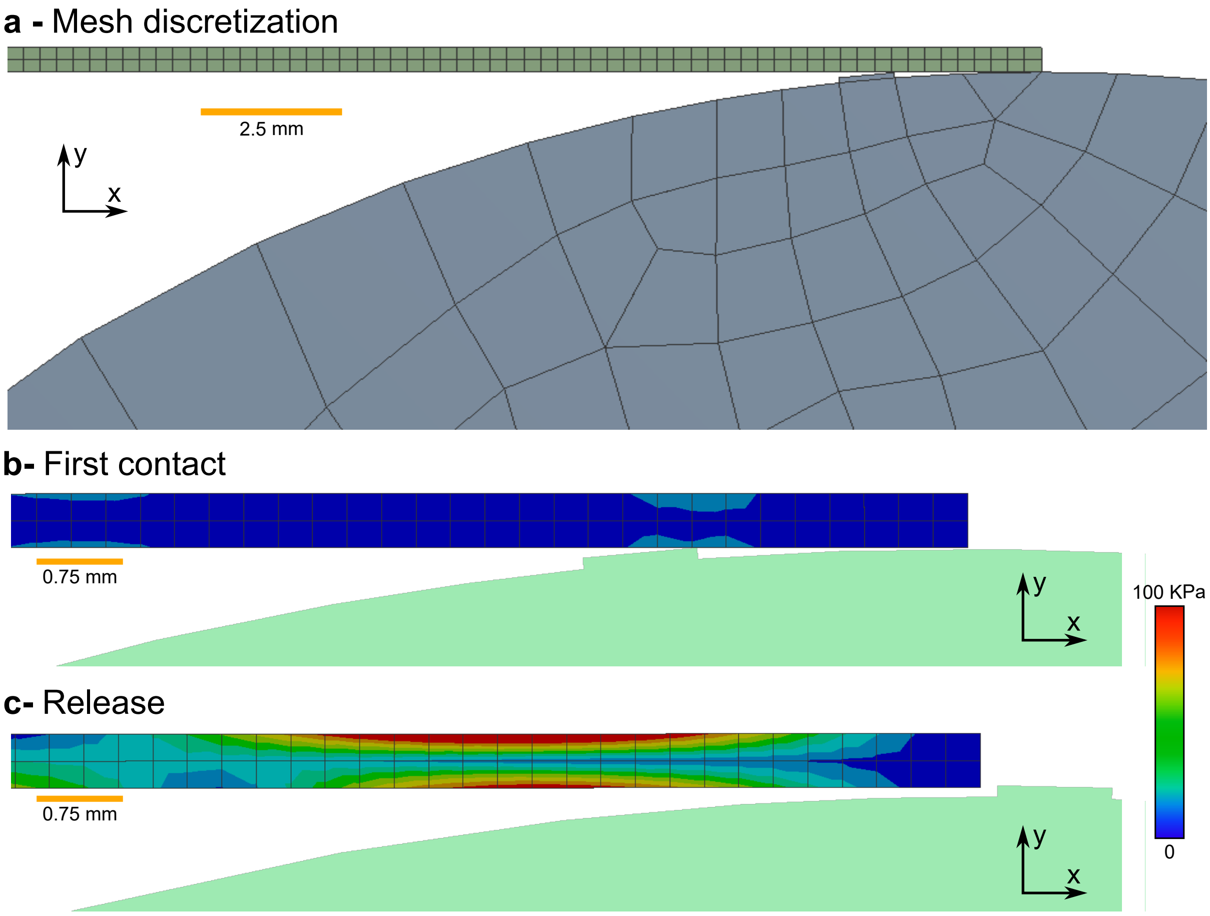

Figure 2: a - The mesh discretization. Grain area, the rest has a similar structure. b - First contact between the pseudo-whisker and the grain (4ms) in terms of the equivalent stress. c - The release of the pseudo-whisker from the grain (52 ms) in terms of the equivalent stress.

To obtain a continuous graph in all cases, we made a cubic spline interpolation between the time steps.

3 RESULTS

Fig. 2b and fig. 2c show the first contact and release between the pseudo-whisker and the grain, at 4 ms and 52 ms respectively. The first contact is when the whisker contacts the corner of the grain. In the simulation, it was observed an elastic wave propagated through the solid. In the first contact, the elastic wave started from the point of contact and traveled until the base, and then it returned. As it swept the grain, more elastic waves were generated that interfered with the returning ones. When the pseudo-whisker released the grain, there was a damped oscillatory motion.

Fig. 3a shows the equivalent stress for the probe nodes. At 4 ms, in the nodes closer to the grain (blue curves), the equivalent stress peaked. Then at 12 ms, there was a maximum peak. The simulation showed that at that moment, the top of the grain made full contact with the pseudo-whisker. As we approach the base (red curves), the graphic shows the maximum peak with some delay, and also, other new peaks associated with the shock waves. After the release (52 ms), there is a dumped oscillation.

Fig. 3b shows the acceleration signal of 3 probe nodes. The pseudo-whisker tip shows neg-

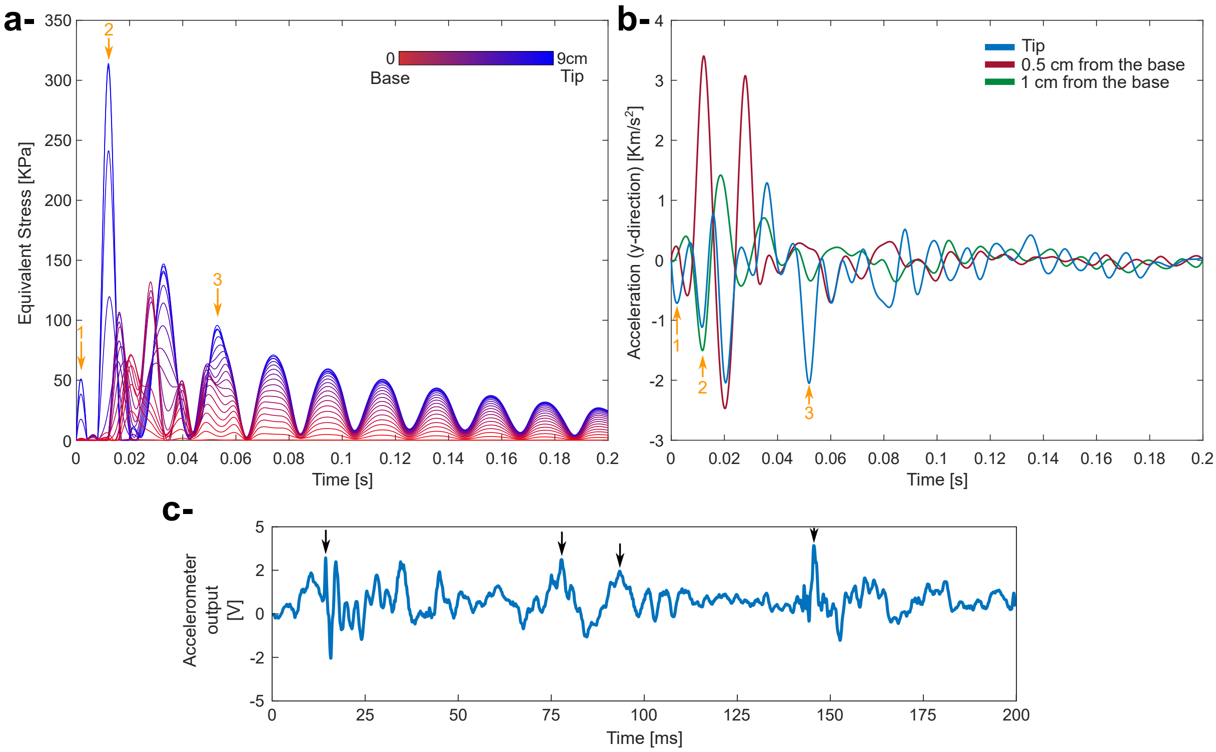

Figure 3: a - Equivalent stress vs time of the 19 probe nodes. b - Acceleration in the y-direction vs time of 3 probe nodes. The orange arrows show (1) the first contact, (2) the contact with the top of the grain and (3) the release. c - Output from the accelerometer of the physical experiment when the pseudo-whisker swept an L120 sandpaper. Obtained from Lucianna (2018).

ative acceleration at the first contact, at 12 ms (contact with the top of the grain), and at the release. As the contact of the pseudo-whisker with the grain was not exactly in the tip, the pseudo-whisker bent, and the tip accelerated in the negative direction in response to this. When the pseudo-whisker released the grain, the whisker returned to the rest state, therefore, we also saw a negative acceleration in that point. After that, the acceleration had a dumped oscillation. The other two nodes in the two contact moments had different behavior, regardless they were close to each other. It is important to note that in none of these nodes was a notable change in the acceleration when the pseudo-whisker released the grain.

4 DISCUSSION

When the rat contacts its whiskers with the environment, the dynamic movement of the whisker reaches the follicle at the base. The mechanoreceptors, by the pressure contact with the vibrissa shaft, detect the activity of the whisker. There is a big difference between the contact with a macro-structure and a micro-structure and it is that, in the first case, the whisker has a noticeable bending and in the second, there is an imperceptible dynamic behavior. In this simulation, we tried to analyze the second situation, with a series of simplifications that allowed us to make our study easier. The key part of this simulation was trying to detect the moment when the whisker collides with a micro-structure, and see if it is compatible with the idea of the slip-stick theory.

The equivalent stress, as proportional of the scalar elastic deformation energy, shows an interesting behavior in the nodes closer to the base of the pseudo-whisker (red curves). Moments after the first contact with the grain, the equivalent stress peaks in those nodes and then it starts to decrease. If the follicle absorbs the elastic deformation energy, the mechanoreceptors can detect the peak which will send a neural spike to the nervous system. Also, as the natural damping is, in magnitude, lower than the collision, it could be conjured that peaks from a certain value could only be detected to avoid false positives by the natural vibration of the whisker.

In the physical experiment, we obtained an acceleration signal of the pseudo-whisker when it swept a sandpaper (Fig. 3c) (Lucianna, 2018). We can compare that signal with the results from the simulation, mainly in the 2 probe nodes closer to the base. Fig. 3c shows a very similar behavior to that obtained in the simulation. That is, peaks with a natural damping. If we correlate the two experiments, we can hypothesize that there are discrete events that are related with the grains of the sandpaper, or in a more general case, between the micro-structures of a texture. Therefore, if the micro-structures are bigger, the events will be bigger (this is a conjecture because we did not simulate with grains of different sizes), and if the micro-structures are closer to each other, the event rate will be higher.

The results obtained here are in line with our findings in the electrophysiological experiments, but we need to develop a model with less simplifications to analyze more situations. Among all the simplifications, the friction could be a very important property to be considered. It was observed that in surfaces of different materials with similar roughness, the rat was able to differentiate between them (Lucianna et al., 2016). This is incompatible with our hypothesis. We believe that the variation in the friction parameters of the different materials could make a difference in the mechanical signal that the rat uses to discriminate the two surfaces.

Also as future development, we are planning to do a FE model of the size of the whisker doing a more profound research in elastic beam models.

ACKNOWLEDGEMENTS

This study was supported by grants from the Agencia Nacional de Promoción Científica y Tecnológica (ANPCYT) and Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), as well as with institutional funds from the Instituto Superior de Investigaciones Biológicas (INSIBIO). The authors wish to thank Gilda Moreno for her assistance with the grammatical review of the manuscript.

REFERENCES

Albarracín A.L., Farfán F.D., Felice C.J., and Décima E.E. Texture discrimination and multi-unit recording in the rat vibrissal nerve. *BMC neuroscience*, 7:42, 2006. ISSN 1471-2202. doi:10.1186/1471-2202-7-42.

Carvell G. and Simons D. Biometric analyses of vibrissal tactile discrimination in the rat. *Journal of Neuroscience*, 10(8):2638–2648, 1990. ISSN 0270-6474.

De la Rama N. and Mendoza A. *Learning Guide in Strength of Materials*. Rex Bookstore, Inc., 1996. ISBN 978-971-23-1999-0.

Diamond M.E. and Arabzadeh E. Whisker sensory system - from receptor to decision. *Progress in Neurobiology*, 103:28–40, 2013. ISSN 1873-5118. doi:10.1016/j.pneurobio.2012.05.013.

Ebara S., Kumamoto K., Matsuura T., Mazurkiewicz J., and Rice F. Similarities and differences in the innervation of mystacial vibrissal follicle-sinus complexes in the rat and cat: A confocal microscopic study. *Journal of Comparative Neurology*, 449(2):103–119, 2002. ISSN 0021-9967. doi:10.1002/cne.10277.

Fish J. and Belytschko T. *A First Course in Finite Elements*. Wiley, 2007. ISBN 978-0-470-03580-1.

Iserles A. *A First Course in the Numerical Analysis of Differential Equations*. Cambridge University Press, 1996. ISBN 978-0-521-55655-2.

Kim J.N., Koh K.S., Lee E., Park S.C., and Song W.C. The morphology of the rat vibrissal follicle-sinus complex revealed by three-dimensional computer-aided reconstruction. *Cells, Tissues, Organs*, 193(3):207–214, 2011. ISSN 1422-6421. doi:10.1159/000319394.

Krubitzer L., Campi K.L., and Cooke D.F. All Rodents Are Not the Same: A Modern Synthesis of Cortical Organization. *Brain, Behavior and Evolution*, 78(1):51–93, 2011. ISSN 1421-9743, 0006-8977. doi:10.1159/000327320.

Lottem E. and Azouz R. Dynamic translation of surface coarseness into whisker vibrations. *Journal of Neurophysiology*, 100(5):2852–2865, 2008. ISSN 0022-3077. doi:10.1152/jn.90302.2008.

Lucianna F., Farfán F., Pizá A., Albarracín A., and Felice C. Functional specificity of rat vibrissal primary afferents. *Physiological Reports*, 4(11), 2016. ISSN 2051-817X. doi:10.14814/phy2.12810.

Lucianna F.A. *Dispositivo biomimético multisensorial táctil para la exploración topográfica de superficies*. Ph.D. thesis, Universidad Nacional de Tucumán, San Miguel de Tucumán, Argentina, 2018.

Mitchinson B., Gurney K., Redgrave P., Melhuish C., Pipe A., Pearson M., Gilhespy I., and Prescott T. Empirically inspired simulated electro-mechanical model of the rat mystacial follicle-sinus complex. *Proceedings of the Royal Society B: Biological Sciences*, 271(1556):2509–2516, 2004. ISSN 0962-8452. doi:10.1098/rspb.2004.2882.

Murphy M.J. Constitutive model parameter determination from generic EFP warhead tests. *Le Journal de Physique IV*, 04(C8):C8–483–C8–488, 1994. ISSN 1155-4339. doi:10.1051/jp4:1994875.

Pizá A.G. *Biomimética neuronal del sistema sensorial periférico de las vibrisas de la rata*. Ph.D. thesis, Universidad Nacional de Tucumán, San Miguel de Tucumán, Argentina, 2018.

Prescott T., Pearson M., Mitchinson B., Sullivan J., and Pipe A. Whisking with robots. *IEEE Robotics & Automation Magazine*, 16(3):42–50, 2009. ISSN 1070-9932. doi:10.1109/MRA.2009.933624.

Quist B.W., Faruqi R.A., and Hartmann M.J.Z. Variation in Young's modulus along the length of a rat vibrissa. *Journal of Biomechanics*, 44(16):2775–2781, 2011. doi:http://dx.doi.org/10.1016/j.jbiomech.2011.08.027.

Schwarz C. The Slip Hypothesis: Tactile Perception and its Neuronal Bases. *Trends in Neurosciences*, 39(7):449–462, 2016. ISSN 1878-108X. doi:10.1016/j.tins.2016.04.008.