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STICK-SLIP BEHAVIOR IN A HUMAN KNEE

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Abstract: *This article brings additional insight to the origin of the so-called patellofemoral crepitus sound observed in a slow-moving knee joint. It has been suggested that this sound is a variant of the so-called stick-slip mechanism known to tribology in different contexts. We provide a deeper analysis of the phenomenon with comparison of measured data and a simplified model. The influence of different parameters like the sliding velocity is discussed. It is shown that the crepitus sound indeed disappears with age and a clinical importance of this find is considered.*
Key words: Knee joint, stick-slip, acoustics and vibration.

1. INTRODUCTION

1.1 Knee auscultation

Knee auscultation techniques (also called knee vibroarthography) have been gaining interest in the past years. Although this method is not yet used clinically, it is believed that it might provide valuable information about knee joint health. Unlike imaging techniques which provide static images of the knee constituents, knee vibroarthography uses the dynamic response of the joint subjected to its natural solicitation. It is believed that this method may bring complementary information to the common imaging techniques. In addition, its prime advantage is its low cost and its non-invasive nature.

The first mentioned use of knee auscultation was provided by Hueter in 1882 [1]. It is followed by early measurement techniques using the first electronic devices by different authors [2-6]. Important change is brought by the introduction of visualizing techniques and numerical analysis of data starting in the late 1980s (Mollan et all. [7]). Since then, the method has been used on many subjects, mostly directed to the distinction between two or more groups of patients with different knee health issues (presented in a review by de Tocqueville [8]). In particular, the problem of patella contact was investigated by Bączkowicz et al. [9]. In this study, chondromalacia, lateral patellar compression syndrome and osteoarthritis were the objects of interest.

1.2 Stick-slip phenomenon

The stick-slip model is known in tribology as being a mechanism of self-induced vibration occurring when two surfaces slide against each other. It is believed to be quite common and can be found in numerous situations: a creaking door, screeching brakes, grinding teeth, a violin bow, an earthquake etc. It is comprehensively explained in the paper by Berman [10].

1.3 Scope of the article

So far, most studies have used the knee vibration data statistically, i.e. without any physical underlying model. Understandingly, this is due to a very difficult modelling of the phenomenon and our limited knowledge of the joint's mechanics. This article tries to partly fill this gap by looking into the **knee crepitus** sound in particular. Knee crepitus was mentioned by Mollan in [7] for the first time

and its nature was correctly attributed to a stick-slip behaviour, but without any further analysis.
Section 2 provides a simplified 1D model that is used to describe the basic behaviour of the stick-slip system. It is then applied to the femur-patella contact problem. Approximate parameters for the model are obtained from experiments or other models specified in the Appendices A and B. In section 4, the potential use of the crepitus is outlined, and the results are discussed.

2. MATHEMATICAL MODEL

This study uses the classic model of stick-slip in 1D represented by the model in Figure 1 below. This model consists of a single mass *m* attached by a spring of stiffness k to a fixed frame. This mass is in contact with the moving support represented by a belt sliding at constant velocity *v*. The mass is loaded by an external normal force *N*. This load generates a tangential friction force *T* at contact point C.
If slip occurs, the motion is described by the one-dimensional second-order equation of motion with the damping coefficient ξ (Eq.1). If stick occurs, the motion is solely governed by the velocity of the belt (Eq.2), i.e. the velocity of the mass is equal to that of the belt. Both equations can be summarized as follows:

slip occurs Eq. (1)
$m\ddot{x} + 2\xi\sqrt{km}\dot{x} + kx = T$ $T = -N\mu_d sign(\dot{x} - v)$
stick occurs Eq. (2)
$\dot{x} = v$ $\lvert T\rvert < N\mu_s$

The necessary condition for stick-slip behavior to occur is a falling friction characteristic, i.e. the static friction coefficient being higher than the dynamic friction coefficient $\mu_s > \mu_d$. The first phase of joint movement corresponds to the moment when the joint contact is subjected to a high load, with very low tangential velocities. Theory then predicts significant hydrodynamic lift, linked to a "squeeze film" effect ([11,12]).

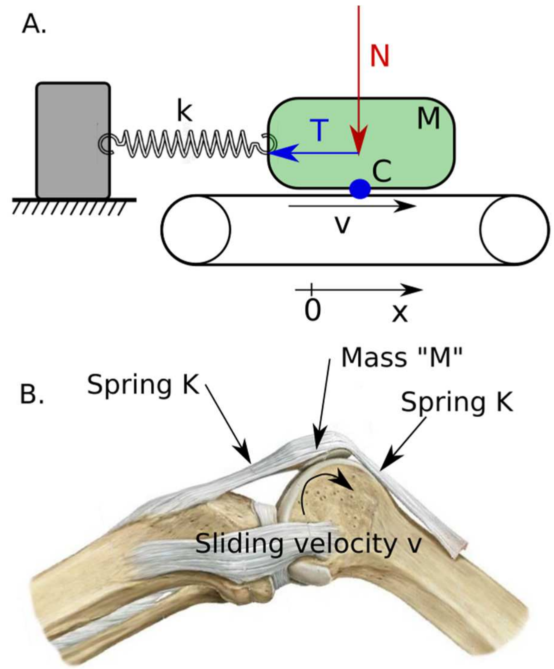

Figure 1A: A simplified 1D mathematical model with a mass sliding/sticking over the moving belt (NB: the orientation of T depends on the relative velocity orientation).
Figure 1B: Model parameters as identified on a real patellofemoral joint (more details in Appendices)

This squeeze effect could be amplified ("boosted lubrication") by an increase in the viscosity of the synovial fluid: the porosity of the cartilage acting as a filter would cause the aqueous phase to leak out, which would tend to progressively increase the concentration of large hyaluronic acid molecules in the synovial fluid, until they are structured into a gel [13]. The high viscosity of this gel enables a high film thickness, of the order of one micrometer, to be maintained at the end of this first phase [14].
This explains the high coefficient of friction at the start of movement. Then, depending on the state of health or pathology of the joint, the coefficient of friction may fall sharply or less sharply. In vitro experiments have shown that this drop characteristic exists in contact with native cartilage [15]. It has been shown that a high concentration of GAGs in cartilage (in the healthy case of a person engaged in regular physical activity) greatly reduces the coefficient of friction. On the other hand, if GAGs are replaced by collagen (the

pathological case of fibrocartilage found in osteoarthritis patients), the reduction in the coefficient of friction is less visible (or even absent). The destruction of the lipid multilayers that protect cartilage in inflammatory pathologies [16] also makes this stick-slip effect less visible.

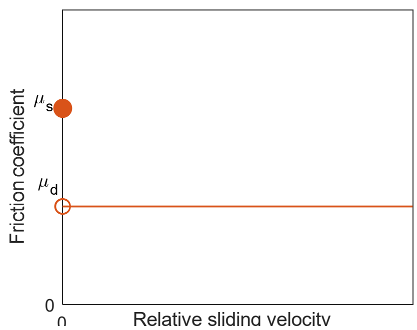

Figure 2: Model of the friction coefficient.

For the sake of simplicity, in the present analysis we consider the model of constant dynamic friction as shown in Figure 2. In this model, we use the following parameters (more details are provided in the Appendices):
The equations 1 and 2 can be solved for a particular initial condition $x(0) = 0$ and $\dot{x}(0) = v$ (initially stick condition is in place) with results shown in Figure 3 in time and state-space domains. In red line, we can see the dynamic behavior of the mass for a low entrainment velocity *v*=5mm/s. In this case, the motion becomes composed of periodic changes between stick and slip phases. The slip starts at point A and continues until the next stick condition is reached at point B. Then, the cycle restarts again. The black dashed line represents the case with higher entrainment velocity v=8.7mm/s parameters unchanged. After the initial stick phase, the slip starts at point A'. Due to higher damping at higher velocities, the body's velocity never reaches again the entrainment velocity and the motion vanishes into the stationary point C.
Apparently, this model predicts a critical entrainment velocity above which the stick-slip behavior is no longer observed. We refer to this velocity as bifurcation point. This point will be of interest in section 3, where we shall try to show its existence experimentally.

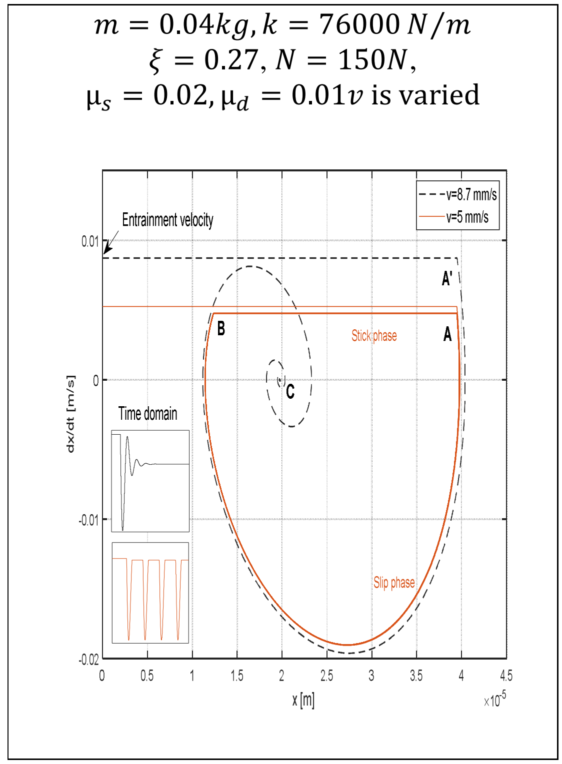

Figure 3: Comparison between simulated stick-slip motion and vanishing motion in state-space representation. The red continuous line shows the case with low entrainment velocity v=5mm/s. Corresponding time-domain waveforms are presented in the bottom left corner.

3. EXPERIMENTAL DATA

The recordings were performed using an analogous microphone PCB 130D21 with amplifier PCB 482C15 and A/D converter Tie Pie Handyscope HS5. The microphone, equipped with a soft plastic bell, was placed freely on the patella as shown in Figure 4. The knee was fitted with a home-made goniometer based on a variable potentiometer. The purpose of this goniometer was to measure the angular velocity of the knee in motion. Several volunteers participated as subjects in the data acquisition, but the data of a single one with the most measurements are presented here.
A typical measurement setup and the measured signals are shown below in Figure 4. The upward motion is naturally irregular, but the volunteers were asked to move their knee in the most constant and linear fashion possible to simplify further analysis.

In order to make comparisons with Figure 3, a crepitus signal was plotted in the time and state-space domain in Figure 5 below. One notices the heart-like shape of the orbits in the state-space domain, which characterizes the stick-slip motion.

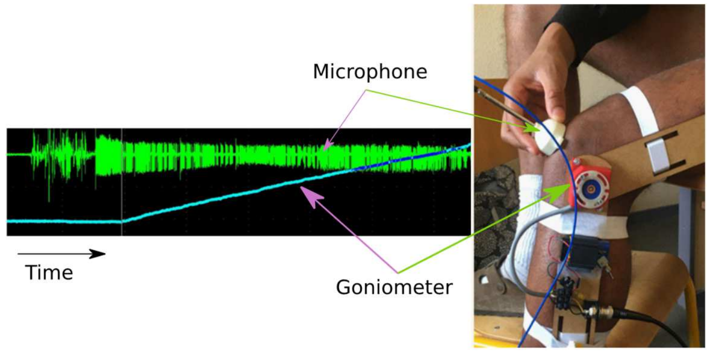

Figure 4: A typical recording of the microphone signal with the goniometer. One can see the outburst of the crepitus from the onset of the motion. On the right, a typical measurement setup: the microphone and goniometer placed on the knee.

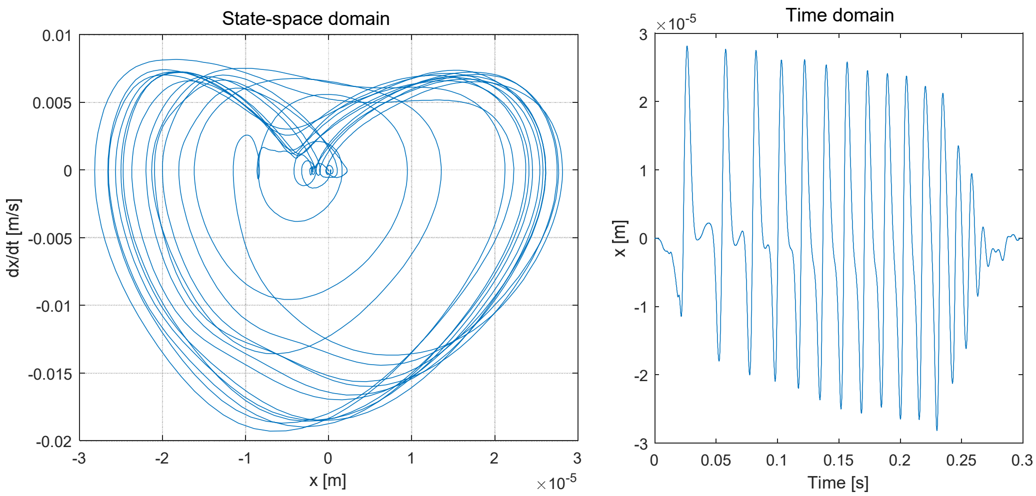

Figure 5: Experimental examples in the state-space and time domains of a sustained crepitus signal. A heart-like shape can be compared to Figure 3.

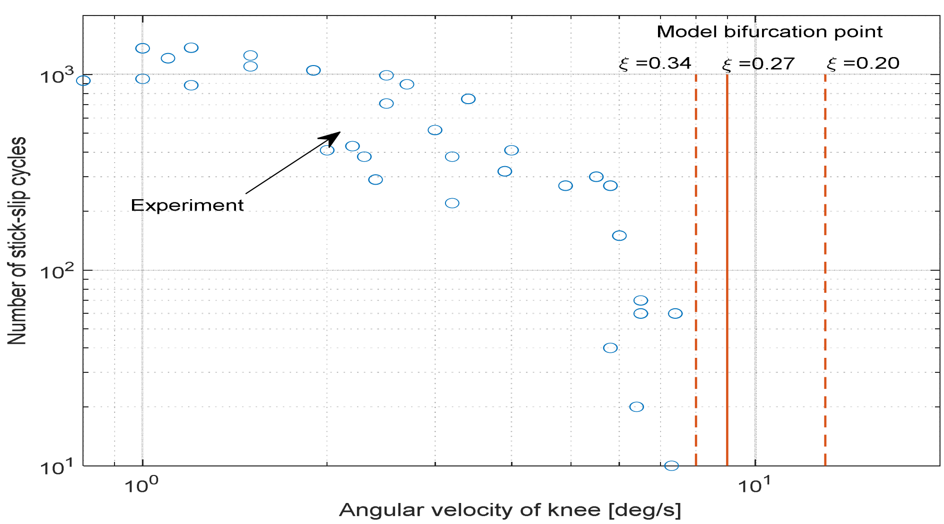

Figure 6: Comparison between experimental data and predicted bifurcation points of the model.

The analysis was performed for different velocities of the knee motion. Using the goniometer, the angular, respective sliding velocity was determined. The number of stick-slip cycles was counted during the entire upward cycle of the knee motion. The downward motions were not used because it was difficult to obtain constant angular velocity.

In Figure 6, one can clearly see the diminishing presence of the crepitus phenomenon with angular velocity. For velocities exceeding 8 deg/s, we do not see any crepitus at all. This result is supported by the mathematical model

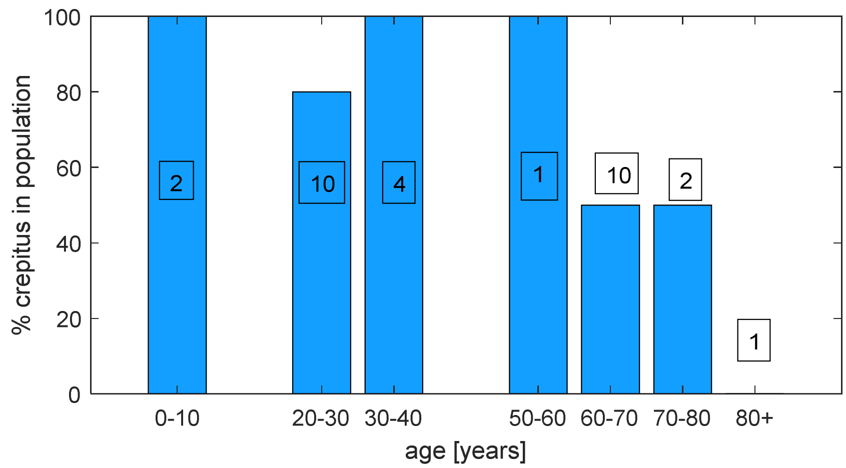

Figure 7: Distribution of the crepitus with age groups. 30 volunteers participated, the numbers in the boxes show the number of subjects in the group.

presented in section 2. According to this model, the bifurcation point between the pure sliding and stick-slip behavior should appear at around 9.5 deg/s. This point is indicated by an orange line in Figure 6. Bifurcation points for damping coefficients 25% lower and 25% higher (i.e. 0.20 and 0.34) are also shown by dashed lines.

4. POTENTIAL USE AND DISCUSSION

Due to its particular waveform, the crepitus sound is very easy to measure and distinguish from other sounds coming from the knee. In addition, it is possible to measure without any instrument. With a bit of practice, a hand placed on the knee can reasonably feel the motion with high reliability. Therefore, it has been suggested to use this phenomenon for the analysis of the knee health state. Surprisingly enough, this noise does not appear with old age, in fact, quite the opposite. It has been found that the crepitus sound tends to disappear with increasing age and is quite rare for elderly people. On the other hand, it is very strong and almost omnipresent for babies and younger subjects (see Figure 7).

It has therefore been suggested to use the **absence of crepitus** as a signal of a knee problem. So far, there is no evidence that this is really the case, however, it is a tempting research topic. The presented article gives a clue about the possible reason of the crepitus disappearance. Looking back at the mathematical model of stick-slip, one notices that the bifurcation point leading to crepitus may disappear for two main reasons:

1. The friction coefficient has equal (or very close) static and dynamic friction. This would relate to a significant change in the synovial fluid and/or contact surfaces.
2. The damping coefficient ξ has increased. However, according to results shown in Figure 6, this would imply a fairly dramatic increase from the nominal value (here equal to 0.27).

Both may appear in aging knees and crepitus may be an easy way to understand a more profound change in the joint, which would otherwise be almost impossible to do.

APPENDIX A – ESTIMATION OF CONTACT FORCES BETWEEN PATELLA AND FEMUR

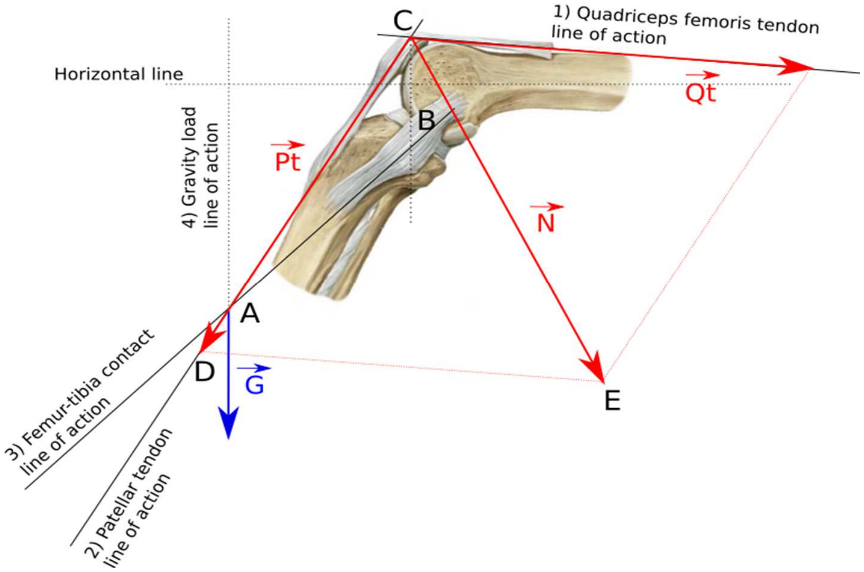

Figure 8 Forces distributed on the tendons considering the tibia, femur and patella bones.

The normal force *N* was obtained by a quasi-static analysis of the lower limb model as shown in Figure 8. Here, all bones are considered as rigid bodies having a single point of contact between them. Tendons and muscles are considered as massless but are able to support forces.

Let us isolate the lower limb and carry on with the static equilibrium analysis. Considering the weight of the lower limb to be concentrated to the center of mass of the lower limb, we obtain a force **G**. Apart from this force, the lower limb is also subjected to a force from the patellar tendon **Pt** and contact force (purely normal for simplicity) between the tibia and the femur. These three forces create a force triangle similar to ABC. From the equilibrium condition, the magnitude of **Pt** can be determined.

Then, we move on to isolate the patella bone. We neglect its weight, but we consider the applied forces from tendons **Pt**, **Qt** and the normal contact force from the contact with the femur **N**. For simplicity, we neglect friction force in the joint, and therefore we have |**Pt**|=|**Qt**|. From the force triangle CDE, the unknown force N can finally be determined. We shall consider this force constant, even though it varies over the motion of the knee.

APPENDIX B– ESTIMATION OF EQUIVALENT MASS, STIFFNESS AND DAMPING

Equivalent mass of the patella was estimated from its static weight. With its volume determined approximately from MRI images and an average bone density taken as $1900 kg/m^3$, we obtained m=40g. Other elements apart from the bone were neglected, even though they may also contribute to the equivalent mass.

The equivalent stiffness k and damping coefficient ξ were estimated from the shock-like response of the patella during its motion on the femur. The cause of this shock is not entirely known, although several mechanical options may be considered, i.e. an uneven surface, instability due to change of contact points etc. Approximately, we may use the same equation 2 to describe the response to this shock:

$$m\ddot{x} + 2\xi\sqrt{km}\dot{x} + kx = T \qquad (1)$$

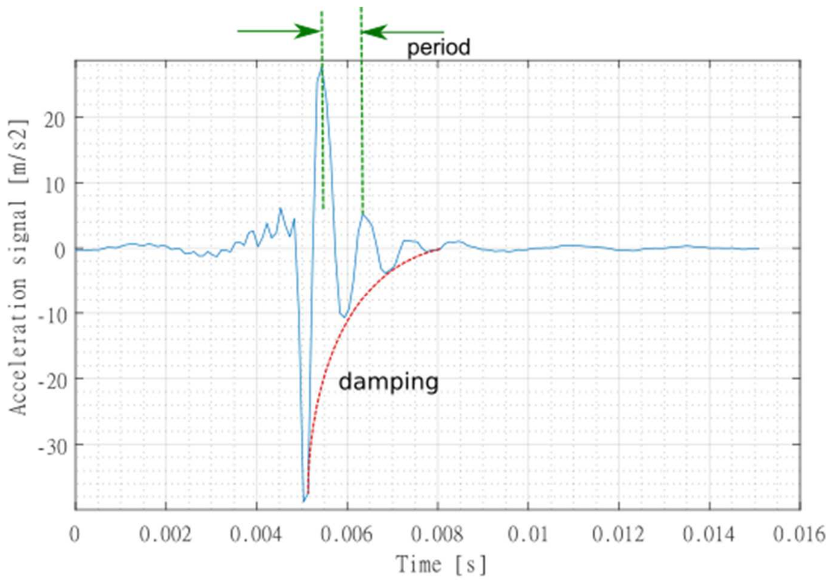

Figure 9 Example of a shock-like response of the patella bone used for the estimation of dynamical parameters.

This time, the right-hand term is not included because only sliding is considered. From the basic analysis of Eq.3, one can notice that the response is a decaying exponential of the form:

$$x(t) = x_0 e^{-\xi t} sin(\omega_0 t + \varphi)$$
$$\omega_0 = \sqrt{\frac{k}{m}}\sqrt{1-\xi^2} \qquad (2)$$

From the experimental data similar to Figure 9, parameters k and ξ can then be determined. In our case, it was found that k=76000N/m and ξ=0.27 on average.

5. REFERENCES

[1] Hueter C., 1882, *Grundriss der chirurgie*, 3rd ed. Leipzig, FCW Vogel

[2] Blodgett, W.E., 1902, *Auscultation of the knee joint,* Boston Med. Surg. J 46-63

[3] Walters C.F., 1929, *The value of joint auscultation*, The Lancet, Volume 213, Issue 5514, Pages 920-921, ISSN 0140-6736, https://doi.org/10.1016/S0140-6736(00)79189-6

[4] Erb K. H., 1933, *Uber die Moglichkeit der Registrierung von Gelenkgerauschen*. Deutsche Ztschr. f. Chir., CCXLI, 237.

[5] Steindler A., 1937, *Auscultation of joints*, The Journal of Bone & Joint Surgery 19(1):p 121-136.

[6] Mang, W., Birk M., Blümel, G., 1980, *Praktische Anwendbarkeit der Phonoarthrographie in der Kniegelenksdiagnostik, Zeitschrift für Orthopädie und Unfallchirurgie*, 118(01): 85 – 90, DOI: 10.1055/s-2008-1051475

[7] Mollan R.A.B, 1981, *Vibration emission in bone and joints*, Thesis (M.D.), The Queen's University of Belfast.

[8] de Tocqueville S., Marjin M., Ruzek M.: 2021, *A review of the vibration arthography technique applied to the knee diagnosis*, Applied Sciences ;11, https://doi.org/10.3390/ app11167337.

[9] Bączkowicz D., Majorczyk E., 2014, *Joint motion quality in vibroacoustic signal analysis for patients with patellofemoral joint disorders,* BMC Musculoskeletal Disorders, 15, 426, https://doi.org/10.1186/1471-2474-15-426

[10] Berman A.D., Ducker W.A., Israelachvili J.N., 2016, *Origin and characterization of different stick-slip friction mechanisms,*

Langmuir 12, https://doi.org/10.1021/la950896z

[11] Dowson D, Unsworth A, Wright V., 1970 *Analysis of 'Boosted Lubrication' in Human Joints*, Journal of Mechanical Engineering Science.;12(5):364-369.

[12] Pascovici M.D., Cicone T., 2003, *Squeeze-film of unconformal, compliant and layered contacts*, Tribology International, Volume 36, Issue 11, Pages 791-799, https://doi.org/10.1016/S0301-679X(03)00095-1

[13] Walker P.S., Dowson D., Longfield M.D., Wright V., 1968, *"Boosted lubrication" in synovial joints by fluid entrapment and enrichment,* Ann Rheum Dis. 1968 Nov;27(6):512-20. doi: 10.1136/ard.27.6.512. PMID: 5728097; PMCID: PMC1010471.

[14] Ateshian G.A., 2009, *The role of interstitial fluid pressurization in articular cartilage lubrication.* J Biomech. 42(9):1163-76. doi: 10.1016/j.jbiomech.2009.04.040. Epub. PMID: 19464689; PMCID: PMC2758165.

[15] Lee D.W., Banquy X., Israelachvilli J.N., 2012, *Stick-slip friction and wear articular joints*, Biophysics and computational biology, vol.110, https://doi.org/10.1073/pnas.1222470110

[16] Ben-Trad L., Matei C.I., Sava M.M., Filali S., Duclos M.-E., Berthier Y., Guichardant M., Bernoud-Hubac N., Maniti O., Landoulsi A., 2022, *Synovial Extracellular Vesicles: Structure and Role in Synovial Fluid Tribological Performances*. *Int. J. Mol. Sci.*, *23*, https://doi.org/10.3390/ijms23191199

Phénomène du stick-slip dans le genou humain / Stick-slip-verhalten bei einem menschlichen knie/ Comportamentul știck-slip în genunchiul uman

Abstract: *Cet article apporte des informations supplémentaires sur l'origine du bruit de crépitement fémoro-patellaire observé dans une articulation du genou à mouvement lent. Il a été suggéré que ce son est une variante du mécanisme dit de stick-slip connu en tribologie dans différents contextes. Nous proposons une analyse plus approfondie du phénomène avec une comparaison des données mesurées et un modèle simplifié. L'influence de différents paramètres comme la vitesse de glissement est discutée. Il est démontré que le son crépitant disparaît effectivement avec l'âge et l'importance clinique de cette découverte est considérée.*

Abstract: *Dieser Artikel liefert zusätzliche Einblicke in den Ursprung des sogenannten patellofemoralen Crepitusgeräuschs, das in einem sich langsam bewegenden Kniegelenk beobachtet wird. Es wurde vermutet, dass es sich bei diesem Geräusch um eine Variante des sogenannten Stick-Slip-Mechanismus handelt, der in der Tribologie in verschiedenen Zusammenhängen bekannt ist. Wir bieten eine tiefergehende Analyse des Phänomens durch Vergleich der Messdaten und eines vereinfachten Modells. Der Einfluss verschiedener Parameter wie der Gleitgeschwindigkeit wird diskutiert. Es wird gezeigt, dass das Crepitus-Geräusch tatsächlich mit zunehmendem Alter verschwindet, und es wird angenommen, dass dieser Befund eine klinische Bedeutung hat.*

Abstract: *Acest articol oferă o perspectivă suplimentară cu privire la originea așa-numitului sunet crepitus femural patello observat într-o articulație a genunchiului cu mişcare lentă. S-a sugerat că acest sunet este o variantă a așa-numitului mecanism stick-slip cunoscut de tribologie în diferite contexte. Oferim o analiză mai profundă a fenomenului cu compararea datelor măsurate și un model simplificat. Se discută influența diferiților parametri precum viteza de alunecare. Se arată că sunetul crepitus dispare într-adevăr odată cu vârsta şi se ia în considerare importanța clinică a acestei descoperiri*

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