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A proposed in vitro model for investigating the mechanisms of 'joint cracking': a short report of preliminary techniques and observations

Jerome CJ Fryer, BSc, DC[1]
Jeffrey A Quon, DC, MHSc, PhD, FCCS(C)[2-5]
Richard D Vann, PhD[6]

Joint "cracking" is common but not a clearly understood audible phenomenon. In this brief report we propose an in-vitro model to potentially assist in revealing a mechanism for, and therefore source of, this phenomenon. Using a suction cup under tension and de-nucleated fluid to simulate synovial fluid, an audible release with intra-articular cavity formation was elicited. This was followed by a refractory period during which no audible crack could be elicited until the observed cavity had slowly reabsorbed back into the joint fluid. Conversely, if regular fluid containing pre-existing nuclei was used, a cavity formation occurred but with neither an audible release nor subsequent refractory period. With this simple in-vitro model, we were able to reproduce the characteristic audible release, cavity formation and related refractory period typically observed in related

Le « craquement » des articulations est un phénomène sonore commun, mais mal compris. Dans ce court rapport, nous proposons un modèle in vitro *pouvant aider à révéler un mécanisme, et par conséquent une source, pour ce phénomène. À l'aide d'une ventouse sous tension et d'un fluide énucléé ayant pour but de simuler la synovie, on a entendu un son provenant de la cavité intraarticulaire, suivi d'une période réfractaire au cours de laquelle on n'a pas obtenu de craquement sonore jusqu'à ce que la cavité observée se soit réabsorbée lentement dans le liquide articulaire. À l'inverse, lorsqu'on utilisait le liquide régulier contenant les noyaux préexistants, il se produisait une perforation de la cavité, mais sans son ni période réfractaire. Ce modèle* in vitro *simple a permis de reproduire le son, la cavité et la période réfractaire connexe caractéristiques qu'on observe en général lors d'expériences connexes sur des*

[1] Private Practice, Nanaimo BC
[2] School of Population and Public Health, Faculty of Medicine, University of British Columbia, Vancouver, Canada
[3] International Collaboration on Repair Discoveries (ICORD), Vancouver Coastal Health Research Institute
[4] Department of Orthopaedics, Spine Division, Faculty of Medicine, University of British Columbia
[5] The Cambie Chiropractic Centre, Vancouver, Canada
[6] Department of Anesthesiology and Center for Hyperbaric Medicine and Environmental Physiology, Duke University Medical Center

Corresponding author:
Jerome Fryer
201-1621 Dufferin Crescent Nanaimo BC, Canada V9S 5T4
E-mail: drjfryer@gmail.com

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experiments in human joints. This simple in-vitro model may be of use in helping to discern both the timing and precise nature of other yet to be discerned mechanisms related to joint cracking.

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KEY WORDS: chiropractic, joint, cavitation, mechanism

articulations humaines. Ce modèle in vitro *simple peut aussi servir à discerner à la fois le moment et la nature précise d'autres mécanismes qu'on n'a pas encore perçus concernant le craquement des articulations.*

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MOTS CLÉS : chiropratique, articulation, cavitation, mécanisme

Introduction

"Cracking" or "popping" is common in many joints, particularly the knuckles, however the mechanisms responsible for the sound remains unclear. In 1938, Nordheim *et al*. used x-rays to investigate joint cracking and observed the presence of intra-articular radiolucencies after joints were moved beyond their normal range of active motion.[1] These lucencies were believed to be due to gas formation, however, no elaborate in vitro model was offered at the time to help explain this phenomenon. Instead, a simple analogy based on a water-filled syringe was proposed. (see Figure 1) In that most basic model, gas formation is reproduced within the syringe by simply pulling on the plunger while the needle end remains sealed. This action generates a bubble that expands in proportion to the increase in volume and corresponding negative pressure created as more tension is applied to the syringe. In accordance with Henry's law of solubility, dissolved gas comes out of solution as greater tension on the syringe reduces its partial pressure. Additionally, in accordance with Boyle's law, the volume of an otherwise fixed amount of undissolved gas increases, again, as its absolute pressure is reduced. Yet gas formation with the syringe model does not generate a cracking sound, and therefore it does not fully explain the events associated with gas formation within joints.

In 1947, Roston *et al*. also detected radiolucencies on x-ray images of cracking joints and hypothesized that they represented bubble formation in the midst of a vacuum created by joint tension or distraction.[2] Roston *et al*. theorized that the bubbles originated from smaller pre-existing gas nuclei (i.e., small spherical bubbles or gas cavities trapped in crevices on hydrophobic surfaces that are ubiquitous in polar fluids such as water), which transitioned to larger visible bubbles at lower vacuum thresholds.[3] These gas nuclei can be dissolved and elim-

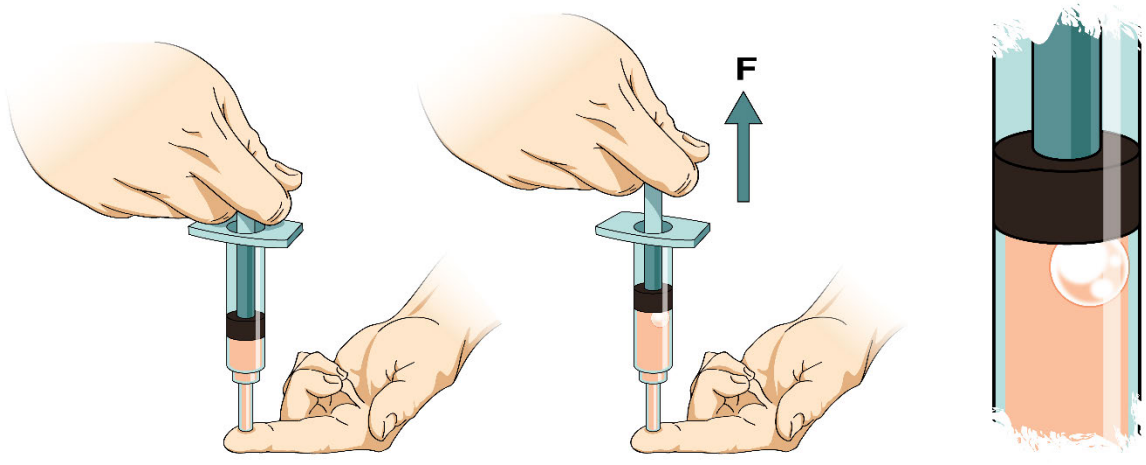

Figure 1.
Water filled syringe under tension.

inated by either hydrostatic compression, boiling at sea level pressure at 100°C, or boiling under high vacuum at room temperature. Although this theoretical framework of denucleation was introduced, no subsequent physical in vitro model evolved from that study.

By 1971 Unsworth *et al*. introduced the 'cavitometre', which was the first in vitro synovial joint model that was developed specifically to study joint cracking.[4] This model was constructed out of nylon and plexiglass with surfaces similar in contour to a metacarpophalangeal joint, only at double the normal size, and separated by synovial fluid. When tension across the system was applied quickly to simulate a joint crack, a cavity appeared and then disappeared. Furthermore, a sound was generated, which the authors concluded was due to bubble collapse rather than bubble formation (the latter of which Roston *et al*. had hypothesized in an earlier study). However, unlike a real synovial joint, the model was open to ambient air, from which gas nuclei could be introduced. Furthermore, the model could be cracked repeatedly without hindrance by any refractory period between sequential iterations.

Irrespective of the model's limitations, the collapsing bubble hypothesis of Unsworth *et al*. remained the most popular explanation for joint cracking sounds for over four decades. However in 2015, Kawchuck *et al*. used magnetic resonance imaging (MRI) to reveal the occurrence of a hypointense area coincidental to the time of a metacarpophalangeal crack.[5] This led to renewed interest in Roston's original theory of bubble formation as a viable alternative to Unsworth's theory of bubble collapse. In further support of Roston *et al.'s* work, Kawchuk *et al*. showed that traction of the finger caused the hypointense area to remain present in the field of view, similar to what is observed in the basic syringe model. But controversy would still exist between the two competing hypotheses as the time window between MRI frames in the study by Kawchuk *et al*. was 0.3 sec, whereas that of the video imaging in the cavitometre study by Unsworth *et al*. was within 0.01 sec.

Kawchuk *et al*. further concluded that the process of cavity formation was likely due to tribonucleation, which by definition is a process of bubble formation from the relative motion of two solid structures under liquid tension.[6,7] However, other studies on tribonucleation do not indicate that this phenomenon is associated with the generation of any notable cracking sounds.[7,8]

To assist in resolving this ambiguity, we describe an in vitro model that possesses three important properties: 1) It is a closed system that mimics the sealed environment of the synovial joint in vivo; 2) It contains de-nucleated fluid and 3) It reproduces both a cracking phenomenon and subsequent refractory period identical to that which is seen in real synovial joints. We believe that this new in vitro model could be a basis for further advancement of previous research on the mechanisms of joint cracking. This improved model simulates much of the natural anatomy and geometry of a real metacarpophalangeal joint. The objective of the current paper is to describe this new-and-improved joint cracking model and to also present some qualitative observations from preliminary tests involving this model.

Materials and Methods

The development of our latest model began with construction of a very basic dry joint model initially (Model A), followed by the sequential construction of 5 additional models (Models B to final Model F). Each model represented a minor modification of the one temporally preceding it.

Model A: Basic dry joint

This model consisted of an elastic suction cup (diameter 10mm) adhered to a polished flat glass plate with an air-filled space simulating a joint cavity. In this model, the suction cup was pressed up against the glass plate, and subsequent traction was applied in two different ways: 1) with just enough tension force to cause partial detachment of the cup (i.e., the centre of the cup) without breaking the seal around its perimeter; and subsequently 2) with greater and sufficient tension to cause the cup to detach fully (i.e., both centre and peripheral margin of the cup) from the glass surface.

Model B: A wet joint

This model was identical to Model A, except that the suction cup was immersed in a beaker of distilled water so that the simulated joint space was filled with fluid. In this model, the suction cup was pressed up against the beaker wall to create a suction adherence, but this time, traction was applied with just enough tension force to cause partial detachment of the cup (i.e. the centre of the cup) without breaking the seal around its perimeter, similar to the first way in Model A.

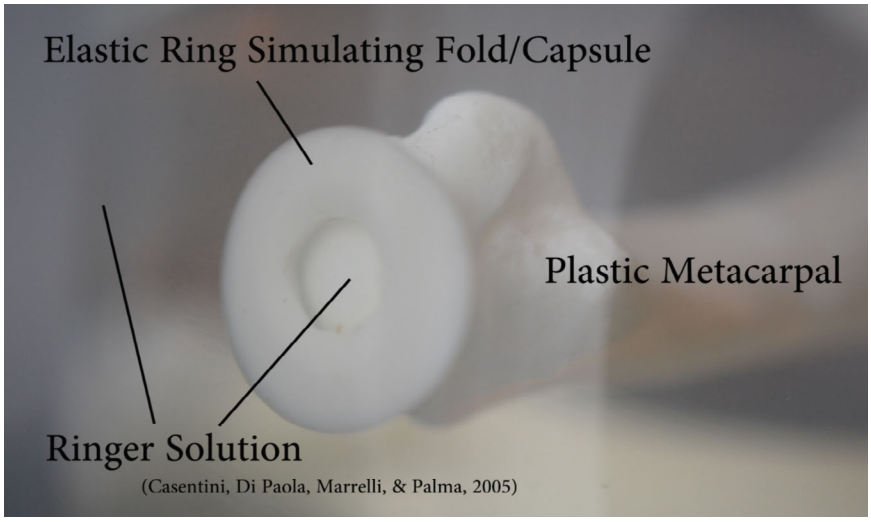

Figure 2.
Model E

Model C: A "de-nucleated" wet joint

This model was identical to Model B, except that the suction cup was immersed in "de-nucleated" distilled water. As mentioned previously, nucleated water refers to normal distilled water, which contains visible bubbles that form through the coalescence of pre-existing gas cavities (i.e., gas "nuclei") within the fluid.[4] These pre-existing nuclei are either smaller unattached spherical bubbles or larger gas volumes that are attached to hydrophobic crevices on solid particles.[9] Both types of nuclei can be partially removed by boiling the fluid for 30 minutes with the suction cup immersed in the fluid and letting cool. Another approach to de-nucleate is by over pressurization[6] and a third approach is by vacuum, which we performed by using -110 kPa for 20 minutes while the suction cup was fully immersed in the fluid. After denucleating the fluid, the suction cup was pressed up against the glass beaker wall to generate a suction adherence. We then pulled on the suction cup with just enough manual force to cause only the centre of the cup to detach from the wall, without compromising the seal around the perimeter of the suction cup.

Model D: A Ringer's solution-filled wet joint

This model was identical to model C, but to more closely simulate the actual fluid in a synovial joint, a Ringer's solution, manufactured as per Casentini *et al*.[10,] was used and de-nucleated as we did with distilled water for model C. Again, after pressing the suction cup to the beaker wall to create a suction adherence, we pulled on the suction cup with just enough manual force to cause only the centre of the cup to detach from the glass beaker wall without compromising the seal around the perimeter of the suction cup.

Model E: Wet joint model with realistic surface geometry

To determine if the cracking event was influenced by the geometry of the suction cup surfaces employed for models A through D, the suction cup was replaced by a polyurethane metacarpal bone. This was achieved by creating a mold of a cadaveric metacarpal bone and pouring an identically shaped polyurethane copy. To roughly simulate the presence of a synovial fold and capsule, an elastic ring was attached to the polyurethane metacarpal head with an adhesive, exposing the central surface of the metacarpal head. This structure was then immersed in a glass beaker with Ringer's solution and de-nucleated under vacuum conditions. After 30 minutes of -110 Kpa the polyurethane metacarpal head was pressed up against the inside of a glass beaker wall while completely immersed in denucleated fluid. (see Figure 2) During testing of this model, we pulled on the polyurethane metacarpal base with just enough manual force to cause only the centre aspect of the metacarpal head to release from the beaker wall, but again without breaking the seal around the perimeter being maintained by the elastic ring.

Model F (Final Model): Compressible wet joint with realistic surface geometry

To test whether changes in joint tension affected the duration required for the model to return to its baseline state (of cavity dissolution) after simulated cracking, a plexiglass apparatus with a fulcrum mechanism was used to apply slight compression to the joint represented by the previous model (Model E). Again, de-nucleated Ringer's solution was used to simulate the presence of synovial fluid. During our tests, we first pulled on the polyurethane metacarpal base with just enough manual force to cause the centre aspect of the metacarpal head to detach from the beaker inside wall below the fluid line, again without compromising the seal around the perimeter of the elastic ring. Following detachment of the metacarpal head and corresponding cavity formation within the simulated joint, we applied compression to the joint model with a clamp (i.e. a fulcrum mechanism), which is depicted in Figure 3. The amount of compression force was not measured at the time, but was subsequently estimated to be between 15 and 30 N.

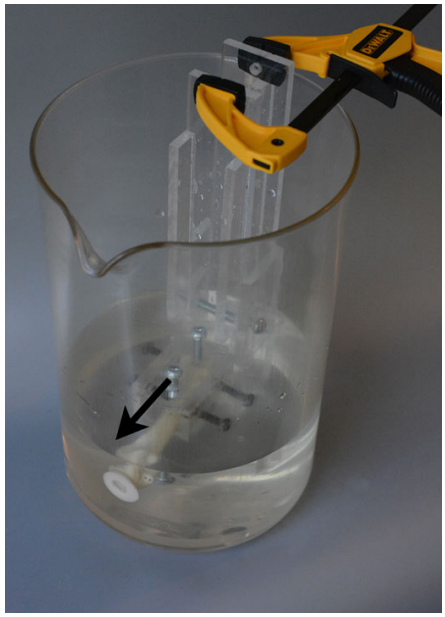

Figure 3.
Compression tension apparatus

Results of preliminary testing

With the Model A dry joint, pulling of the suction cup to detach only the centre aspect of the suction cup was not associated with an audible event. Only with further traction and detachment of the cup perimeter did a cracking sound occur.

With the Model B wet joint, as the suction cup was slowly pulled from the inside of the beaker wall in its closed state, a gas cavity formed silently as the centre of the suction cup detached without breaking the seal around its perimeter. Furthermore, when tension was subsequently reduced in order to allow the suction cup to return to its previous neutral position, the cavity disappeared (as

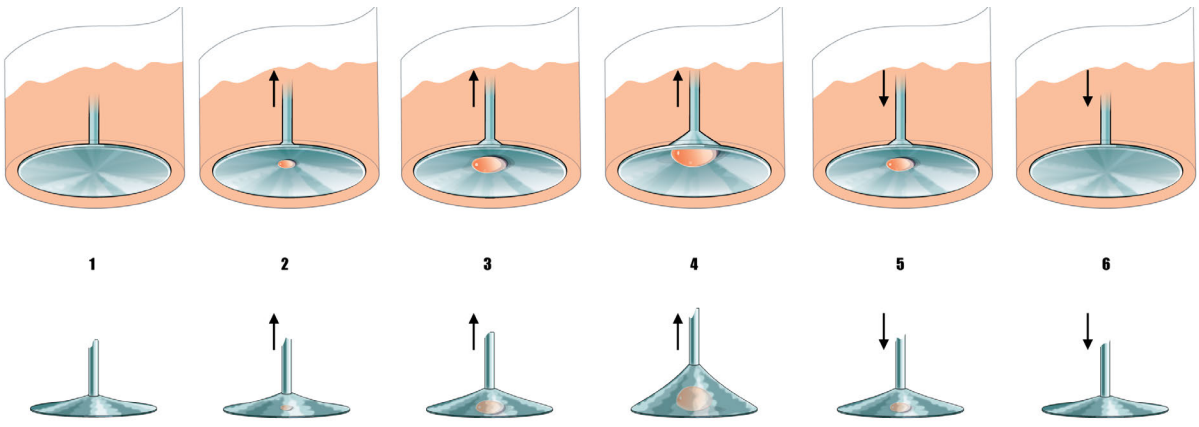

Figure 4.
Model B. Within a simulated wet joint space (without de-nucleated fluid) in a sealed condition (1), decompression and volume expansion results in expanding bubble formation (2-4) while return to initial tension and volume normalization results in bubble disappearance (5-6).

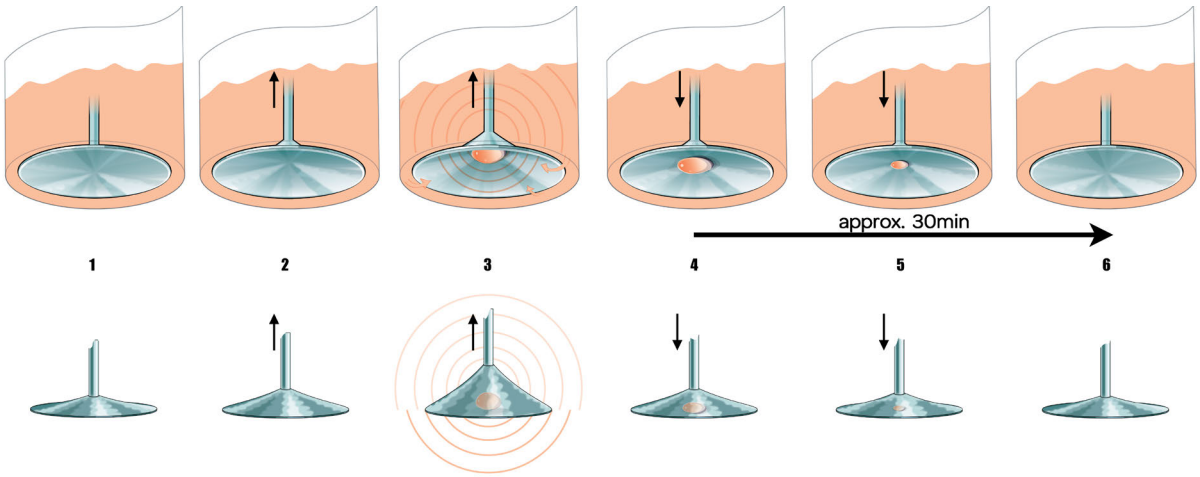

Figure 5.
Model C Within a simulated wet joint space (with de-nucleated fluid) in a sealed condition (1), decompression results in suction cup stretch without lift and without cavity (2). Suddenly, when sufficient tension is applied a cavity and sound spontaneously forms (3) and further decompression leads to increasing cavity volume formation. Relaxation of tension leads to enduring cavity (4) and over time, cavity size shrinks (5-6). The sequence 1-6 can then be repeated.

was expected under Boyle's Law, which describes the inverse relationship between pressure on the one hand and volume of an otherwise fixed amount of undissolved gas on the other hand). This sequence of events is depicted in Figure 4.

With Model C in which distilled water within the simulated joint space was replaced by de-nucleated water, neither central cup detachment nor gas cavity formation was observed when the suction cup was pulled with the same initial force as was used in Model B. In other words, with initial tension the centre of the suction cup did not release from the beaker wall but instead remained completely adherent to it. It is noteworthy that in the previous model employing nucleated fluid (Model B), bubble formation was observed immediately during traction, whereas in Model C employing denucleated fluid, gas bubble formation was no longer evident early on. Only later with Model C, when the suction cup was pulled with greater force did its centre detach from the surface. Moreover, upon detachment, a stable gas cavity formed in association with an audible crack. Also with Model C, when the suction cup was released and allowed to return to its baseline position, a visible cavity remained, and then disappeared only gradually over approximately 30 minutes. Finally, so long as a bubble or cavity remained visible to the naked eye, no further cracking sound could be elicited during re-pulling of the suction cup. On the other hand, once the bubble was no longer visible to the naked eye, an audible crack could again be elicited from the model (Figure 5).

With Model D, we observed the same findings that we observed during experiments with Model C. More specifically, the experiment with de-nucleated Ringer's solution resulted in joint cracking and a corresponding refractory period that was identical to that of a model employing de-nucleated distilled water.

With Model E, regardless of whether the joint was immersed in nucleated distilled water or nucleated Ringer's solution, the observed events were identical to those that were observed in Model B. In contrast, when either the distilled water or Ringer's solution was de-nucleated, our observations were identical to those obtained with Model C.

Under Model E, we also were able to generate the cracking sound when the model was pulled off-axis, which we did in order to simulate cracking of a real knuckle joint in a partially flexed or non-neutral position (https://youtu.be/TzC7PkgbHGA).

With our final model, Model F, the application of com-

pression through the joint (subsequent to cavity formation and an audible release) resulted in a reduction in the time required before cavity formation and joint cracking could be repeated. In this regard, the so-called refractory period without compression was previously 30 minutes, whereas the refractory period with joint compression was only 12 minutes. Qualitatively, we observed that the greater the amount of compression that was applied to the model, the shorter was the refractory time.

Discussion

We have introduced a series of in vitro models and a final model that will serve as a basis for our future investigations into the mechanisms of synovial joint cracking. Our observations at this time are too anecdotal to warrant a full report, however they are presented here for the purpose of soliciting immediate comments and criticisms from the broader research community. In the meantime, a key preliminary finding is that the events we observed after replacing regular fluid with denucleated fluid (in Models C, D and E) are completely consistent with the same cavity formation and refractory period phenomena that is associated with the cracking of real synovial joints. Specifically, within a closed system employing denucleated fluid, as long as a bubble or cavity formation is visible within the simulated joint space, a crack can not be repeated. In contrast, once the cavity disappears, a crack can again be elicited from the model.

This behaviour of gas within liquid is typically interpreted to reflect the dissolution of a spherical bubble by the forces of surface tension. Until its dissolution, a bubble acts as a gas nucleus (as observed in Model B) which permits formation of a larger visible gas cavity during decompression of liquid within a closed system, but in the absence of generating an audible crack. Epstein and Plesset derived equations that describe the time to dissolution of a bubble in relation to absolute pressure, dissolved gas tension, and surface tension.[11] Accordingly, in Model F, a reduced refractory period was both expected and observed, and ultimately reflected faster re-solution time in response to increased local absolute pressure.

Admittedly, the precise timing of the crack in relation to the timing of bubble formation was not discernible from these preliminary experiments. At this time, it remains a mystery whether sound generation occurs before, after, or simultaneously to the time of cavity formation. The timing of the crack in relation to bubble formation will be the focus of our future work. Additionally, we plan to quantify corresponding forces, tensions, bubble sizes, and dissolution times through the use of multiple imaging methods (i.e., cinematography, ultrasound, and MRI).

Conclusion

In this brief report, an in-vitro model has been developed and proposed to investigate the origins of the cracking sound within synovial joints. So far, we have observed that when a de-nucleated fluid is introduced, decompression of a sealed joint elicits both cavity formation and an audible event, similar to what occurs in human synovial joints. Immediately afterward, a refractory period occurs during which an additional audible event cannot be elicited regardless of how much joint decompression or tension is applied. In contrast, if the fluid used in the model is nucleated, decompression of the simulated joint elicits cavity formation in the absence of an audible event. Additional measurement techniques will be developed and applied to this new model with the intent of better clarifying the mechanisms of in vivo joint cracking.

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References

1. Nordheim, Y. Einer neue Methode den Gelenkknorpel besonders die Kniegelenkmenisken röntgenologisch darzustellen. Fortschr Röntgenstr 1938;57:479.
2. Roston JB, Haines RW. Cracking in the metacarpophalangeal joint. J Anat. 1947; 81: 165–173.
3. Harvey EN, et al. Bubble formation in animals. I. Physical factors. J Cellular Comp Physiol. 1944; 24(1):1-22.
4. Unsworth A, Dowson D, Wright V. 'Cracking joints' A bioengineering study of cavitation in the metacarpophalangeal joint. Ann. Rheum. Dis. 1971; 348–358.
5. Kawchuk GN, Fryer J, Jaremko JL, Zeng H, Rowe L, Thompson R. Real-time visualization of oint cavitation. PLOS ONE. 2015; 10(4): e0119470.
6. Hayward AT. J- Tribonucleation of bubbles. Brit J Appl Phys. 1967;18:641-644.
7. Wildeman S, Lhuissier H, Sun C, Lohse D, Prosperetti A. (2014). Tribonucleation of bubbles. Proc Natl Acac Sci USA. 2014;111(28):10089–10094.

8. Ikels KG. Production of gas bubbles in fluids by tribonucleation. J Appl Physiol. 1970; 28(4): 524–527.
9. Marschall HB, Mørch KA, Keller AP, Kjeldsen M. Cavitation inception by almost spherical solid particles in water. Phys Fluids. 2003;15(2): 545.
10. Casentini G, Di Paola L, Marrelli L, Palma F. Rheological characterization of an artificial synovial fluid. Int J Artif Organs. 2005;28(7):711-717.
11. Epstein PS, Plesset MS. On the stability of gas bubbles in liquid-gas solutions. J Chem Phys. 1950; November 1.