The present work was submitted to Visual Computing Institute

Interaction in Virtual Worlds
Pro-Seminar Summer Term 2022

Simulating Stiffness of Virtual Objects with Haptic Jamming Devices: An Overview

Seminar Thesis in Computer Science by

Louis Wellmeyer
Student ID Number:434261

Prof. Dr. Torsten W. Kuhlen
Virtual Reality & Immersive Visualization

Supervisor:Martin Bellgardt

Aachen, June 30, 2022

Contents

1 Introduction

Part of our haptic perception is feeling the texture and temperature of things, perceiving weight, grasping different shapes and volumes, and experiencing an object's pressure and hardness. We have only achieved to enable the perception of a small number of our senses in virtual reality, yet even less are available publicly outside of research. There have been only a few attempts to achieve the named aspect of stiffness perception of objects in virtual reality, with rarely trying to create handheld devices. This paper presents how the phenomenon of jamming can be utilized to enable this perception in virtual environments and how it can be integrated into handheld devices. Jamming allows us to alter the stiffness of materials inside a flexible membrane by regulating pressure. Furthermore, jamming is excellent not only for its potential to experience the sensation of hardness, but it can also be used to shape objects and convey force-feedback. Additionally, it consists of only a few, mostly natural and inexpensive components, which allow haptic devices with the proposed jamming concept to be inexpensive compared to other products in the VR Marketplace. With the aim in mind to contribute to the eventual creation of multimodal haptic devices that cover each named property of the human's sense of touch, I describe in detail how one may integrate jamming as a procedure into today's popular designs of handheld devices while trying to deliver a highly immersive virtual reality experience. In the process, commonly used materials, shapes, and sizes for jamming are evaluated with each other using existing studies and experiments in Chapter 3.4. Doing so will ascertain which materials and overall design will convey the most pleasant and immersive user experience.

2 Related Work

Stiffness perception is crucial for fully implementing the sense of touch in virtual environments. In the following, three glove-based haptic device designs that use jamming and one design with an alternative approach, tightening fabric, are presented.

2.1 Prior Implementations

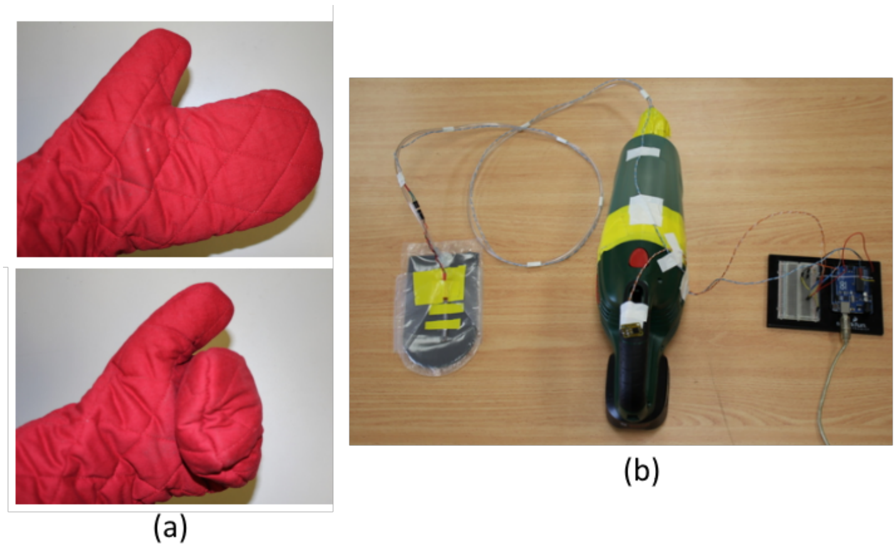

Figure 2.1: [Simon et al., 2014] design of a kitchen mitten with force-feedback using layer jamming. a) The mitten; b) its jamming system: the jamming membrane with sandpaper layers, vacuum pump (Bosch model PAS 18LI), and a Arduino Uno that is connected to a computer (not in image)

[Simon et al., 2014] examines the integration of haptic technologies into wearable computing forms like cloth and gloves. Their goal is to provide computer-controlled haptic stimulus to user movement. They conducted their own implementation using layer jamming: A 2.1 mm thick polyethylene and nylon membrane containing eleven layers of wet-dry sandpaper was attached to an ordinary kitchen mittens inner palm (see Figure 2.1a)). A pipe at about the wrist connects the contents of the membrane with a handheld vacuum pump. Additionally, cables run from a flex sensor at the back of the mitten into an Arduino microcontroller that turns on and off the pump (shown in Figure 2.1b)). In a study, six adults compared the touch sensation of a physical object and a virtual one while wearing the mitten. The participants were either holding a pole supported by the jamming of the glove, holding a pole without jamming or only having jamming activated without holding the pole. With their eyes closed, they had to rate on a five-level Likert scale, with 0% being 'strongly disagree' and 100% 'strongly agree', if their feeling was similar to their tests prior and if they felt realistic. Except for one person, everyone else said their experience to be similar each time, and an average rating of 69% was evaluated regarding the realism of their haptic perception. The participants were overall positively surprised.

Two implementations of stiffness perception in gloves have been designed and are presented by [Zubrycki and Granosik, 2015]. In addition to the ability to sense hardness, both implementations restrict the user's finger movement when jammed, resulting in force feedback. With their designs, they aim to refine the teleoperation of robotic grippers through kinaesthetic feedback and increase their availability through a cheaper alternative compared to current expensive kinaesthetic feedback devices. Their first design consists of an elastic glove with small jamming areas under each joint. By changing the stiffness of those, the ability to grasp is controlled due to the restrictions of closing one's hand. This results in a simulation of holding objects with different elastic properties. One issue is that the stiffness can only be perceived by closing the palm. In an attempt to solve the named issue, the alternative of having jamming tubes running along the whole finger instead of just the joint is presented. Despite now disallowing movement of fingers in specific other directions when jammed, it cannot constrain movement of individual joints independently. Zubrycki and Granosik further suggest the incorporation of small vibration motors onto the user's fingertips. According to them, it would benefit the user by notifying him or her when getting into contact with an object and it would enable texture perception.

In contrast, [Bianchi et al., 2016] presents a fabric-based wearable haptic device for actively and passively perceiving stiffness. The device is put onto the user's finger with an elastic clip. It achieves active stiffness feedback by two DC motors independently moving rollers attached to an elastic fabric. The user actively experiences different stiffness levels by moving their finger joints. With the use of a servo motor, the fabric can be lifted, fixing the user's finger and delivering tactile cues to the skin. The fabric wrapped around the finger increases applied force on the user and limits control of force as well as stiffness. Due to the independent control of the DC motors, a sideways sliding effect can be initiated. The device's effectiveness was shown in experiments with fifteen healthy participants who conducted recognition tests. The participants had to identify silicone specimens with different stiffness levels based on their perception of the artificially created rigidity of the finger device. The lowest average accuracy of all recognition tests was 82.22%, scored in the active recognition test, where participants had to match their perceived stiffness to one of three physical silicone specimens. The highest average accuracy with 91.11% has been achieved in the active test of sorting three randomly given stiffness levels based on their perception induced by the device. In a rating of the sliding sensation, using a bipolar Likert-type seven-point scale, an average score of 6.67 ± 0.65 was scored, excluding low scores of 3 and 2 of three participants with smaller fingers. Overall, these results imply an effective sensation of named haptic cues.

3 Perceiving Stiffness Of Virtual Objects

In order for the virtual reality system to be highly immersive, the user needs to be able to interact with objects in virtual environments and receive, optimally, instantaneous feedback. The device used by the user for interactions should be as light and small as possible so that the user, at maximum, barely notices he's/she's carrying a device. This chapter reports how stiffness perception can be realised in haptic devices while upholding a light weight and compact design. Furthermore, an overview of influences on the performance of stiffness perception is given to create the best devices that will deliver a great user experience.

3.1 Jamming

In jamming, a membrane made of flexible material (e.g., silicone, rubber, elastomers) embraces granular or, in the case of layer and fibre jamming, respectively, fibres and thin sheets. Through a controlled air pump in most designs, the cell can be vacuumed, contracting the inner surface of the membrane, resulting in the clamping of the inner material, disallowing their movement among each other, and making them appear hard. Jamming with the use of a pump is referred to as pneumatic jamming. Alternatively, hydraulic cylinders can be used to control the density of liquids inside the jamming chamber to achieve different rigidity levels. The use of hydraulic cylinders for jamming is called hydraulic jamming.

We come across the jamming phenomenon in many situations in our daily life. For instance, when bought, potting soil feels rather stiff since the individual movement of grains is restrained by its packaging. When removing the package, one is left with only the soil that now behaves almost fluid-like.

Jamming originates from Soft Robotics which traces back to 1978 when the first gripper that makes use of granular jamming for improved grasping was presented [Schmidt, 1978]. An obvious approach for a robot to grab and hold objects is to have human-like hands with fingers. In recent years, work regarding jamming was picked up again and continued. Thus jamming as a concept was better understood. As a result, [Brown et al., 2010] introduced a less complex approach that abolishes many challenges and hardware as well as software complexities of the former implementations. Instead of having multiple fingers which joints and pressure need to be controlled individually, they put forward a design of a universal robotic gripper with a sphere-shaped granular mass using jamming to deform around an object and grab it by making the granular rigid through vacuuming (see Figure 3.1).

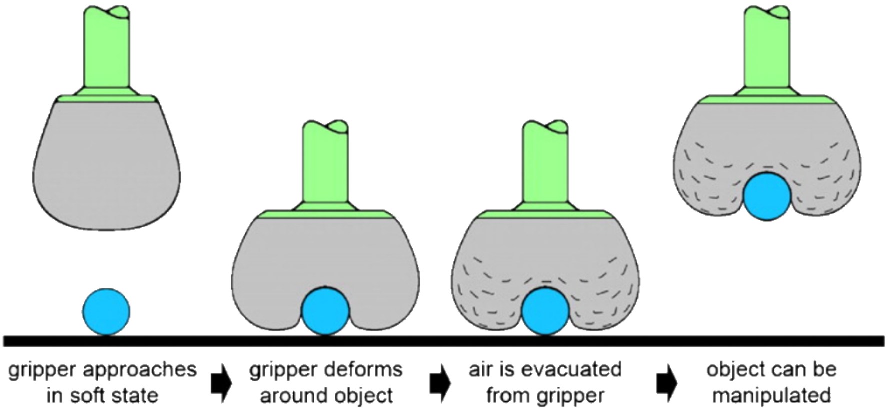

Figure 3.1: Eric Browns et al. design of a universal robotic gripper using granular jamming [Brown et al., 2010].

According to [Follmer et al., 2012], the amount of fluid volume, V_r, that needs to be sucked out of the cell for a pneumatic jamming system to jam, can be approximated as

$$V_r \approx V_b - V_g(1 + \frac{0.36}{0.64}) = V_b - \frac{m_g}{rho_g} \cdot (1.5625) \tag{3.1}$$

with V_b being the current volume of the jamming cell and V_g the volume of the granules, m_g its mass and rho_g its material density. The time, t_r, needed for the system to jam is defined as follows:

$$t_r = \frac{V_r}{Q_p}. \tag{3.2}$$

Qp is the pump's volumetric flow rate.

Hysteresis means for a value to depend on its history and current state of execution. Many physical phenomena display some form of hysteresis. Some instances where hysteresis occurs are Schmitt triggers, magnetization, and, in our situation, applied forces to elastic materials. An easy example that greatly explains the concept behind hysteresis provides [Garbe, 2020] (see Figure 3.2): A thermostat that controls the temperature inside a home is supposed to maintain a given room temperature named T_{comfy}. Without hysteresis, the heating would constantly change between on and off. Because that would be very inefficient and vulnerable to break, hysteresis is manually implemented. When the room temperature reaches a maximum value, T_{high}, the heating will be turned off for the room to cool down. Now, if the temperature falls below a lower threshold, named T_{low}, the heating will be turned on again. As a result, depending on the direction of the curve (in Figure 3.2), the thermostat can have two different values. The value of the hysteresis - the difference in both values - also referred to by H, is calculated with the following equation:

$$H = \frac{A_{On} - A_{Off}}{A_{On}} \tag{3.3}$$

where A_{On}, A_{Off} are the area of the curves. To note, generally, H is a normalized value between 0 and 1. 0 means no difference between both curves, while 1 states the highest possible difference. When hysteresis unintentionally occurs, generally, one will try to maintain its value low. A low hysteresis means for jamming to be more controlled and consistent. Thus studies strive to find out what the hysteresis is affected by and how to minimize it.

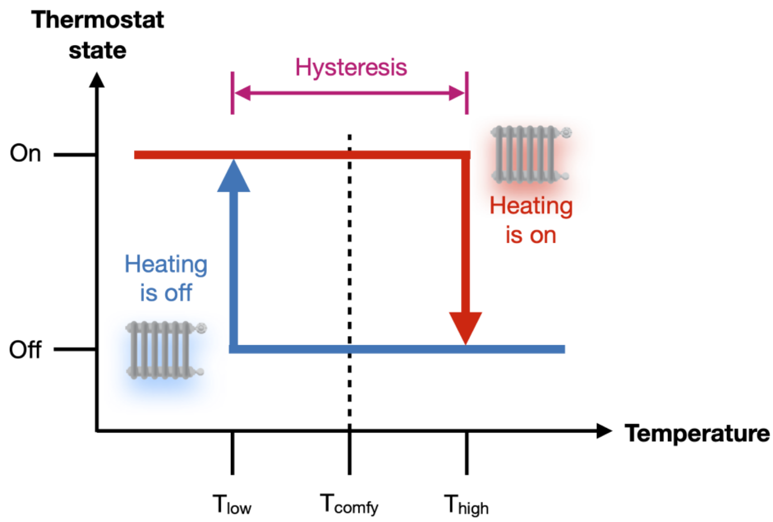

Figure 3.2: Simple example diagram featuring hysteresis of a thermostat for regulating temperature. Credit: [Garbe, 2020].

3.2 Advantage

A different approach for simulating stiffness is through thin films of a garment, as presented in Chapter 2. The downsides of the proposed system are its essential requirement in parts and engineering, resulting in a notable device size just for one finger. On the other hand, jamming only needs grains, e.g. ground coffee, a membrane that can be as simple as a publicly available latex or rubber balloon, and a way to jam the composition like a syringe.

Furthermore, [Bianchi et al., 2016]s proposed device lacks reliability for different hand sizes, a common trait of wearable devices. Jamming is not bound to a wearable implementation and thus can be versatile. Frequent implementations in terms of haptic that use jamming are desktop devices (e.g. as featured in [Stanley and Okamura, 2017]), hand-held devices, and, most commonly, wearable devices like gloves (see Section 2). There is also potential for more designs as seen on jamming's origin, robotics, where it is is used for various purposes, like generic grabbing as proposed by [Brown et al., 2010], and for invasive surgeries like [Kim et al., 2013] presents.

Not only can jamming enable stiffness perception, but a feature that jamming also enables is the ability to recreate the shapes of virtual objects through the combination of pneumatics to inflate the jamming surface and obtain different geometries. The shape manipulation is out of scope for this paper, though it has been explained in [Stanley and Okamura, 2017] to a great extent. Another aspect jamming functions for is force feedback. Hardening shapes allow for restricted hand movement. This can be exploited to achieve force feedback, similarly to how Timothy M. Simon et al. [Simon et al., 2014] designed their force feedback mitten, introduced in Section 2.

3.3 Challenges

One challenge is the requirement of a pump for pressure regulation of the jamming cells. Required is a solution where possibly multiple pumps control the pressure of individual cells without making the devices with integrated jamming too heavy and not have many pipes and wires, which would ultimately end up in an unpleasant experience for the user.

On top of that, the required powering of the pump proposes a challenge and the noise generation of the operating pump is an aspect that needs to be resolved in the future. Proposed ways to possibly cope with the named issues are micro vacuum pumps and hydraulic jamming, as stated by [Simon et al., 2014]. In hydraulic jamming systems, hydraulic cylinders replace the pump required for regulating air entirely and swap the air of the jamming chamber with a liquid (e.g. oil). Also, with the use of hydraulic cylinders, the system would be able to maintain pressure without requiring power. According to [Simon et al., 2014], the hydraulic cylinders will probably operate silently. [Jiang et al., 2013] addresses the idea. With a similar

vision, they present how a hydraulic granular joint of a snake-like surgical robot can be jammed by depriving deaired water instead of air. Oil would most likely be more applicable since it can create a uniform and consistent density easier. Converting into a water-based hydraulic system allowed the detachment of the snake-robot from the system. Nevertheless, the same stiffness level was achieved with deaired water, and even less volume is required. Additionally, they found that a 50% lower stiffness can be achieved than with pneumatic systems. Some granules may be susceptible to cohesion or other inter-particle forces when introduced to a fluid to attain even better stiffness levels.
Tests with the hydraulic and pneumatic systems were performed individually by [Jiang et al., 2013] to compare the two. For the experiments, hemispherical acrylic granules of 1 mm in diameter were used inside a latex cylinder of 10mm in diameter and 33mm long with 0.2mm thick membrane walls. All experiments examined the stiffness and hysteresis. The pneumatic system was tested without applying pressure by applying continuous vacuum draw and was tested where a syringe replaced the pump, extracting 10 mL air. The first named test (Figure 3.3 (a)) resulted in a low stiffness of 0.08 N and a hysteresis of 11%. A force of 0.32 N resulted in a stiffness deflection of 10 mm and a hysteresis of 80% in the second test (Figure 3.3 (b)). The Syringe achieved the same deflection with 0.21 N with a hysteresis of 73% (Figure 3.3 (c)). The hydraulic unjammed test (Figure 3.3 (d)) resulted in hysteresis of 21% with a 0.04 N peak stiffness. In the last test (Figure 3.3 (e)), an extraction of 0.5 mL of water jammed the cylinder. Even though that is 20 times less extraction than in the pneumatic system, it yielded a similar result. However, that means that not much liquid is required in a hydraulic system. Therefore, the evacuation chamber can also be small and does not require a big pump with an air chamber.

According to [Jiang et al., 2013] the apparent downside of hydraulic jamming systems is that, in case of any leaks inside the system, it becomes completely unusable while on the other hand, in a pneumatic system, only the stiffness performance suffers, but overall remains usable because the jamming joint would still be able to stiffen after an influx of air.
Another possible disadvantage is the additional water weight for each jamming joint compared to having a pneumatic system. Despite that, the overall system weight decreases vastly, even when having water, since no pump is needed, and the joint weight only increases slightly due to not requiring an immense amount of liquid as stated before.

Unidirectional feedback is difficult to avoid when designing jamming devices, especially for handheld ones that do not fully surround a body part, essentially for ones that are not worn by the user. For example, will controllers with jamming areas most likely only allow stiffness perception for the palm and finger joints of the user but not his/her backhand.

Jamming overall faces the additional challenge for small jamming areas to provide a low minimum stiffness and high rigidity ranges. This can be seen with the increase in Young's modulus value E as the object's size decreases, but the applied force remains the same. As a result, an object increases in pressure resistance. An explanation of Young's modulus and a more detailed analysis of how jamming influences E follows in Section 3.4.3.

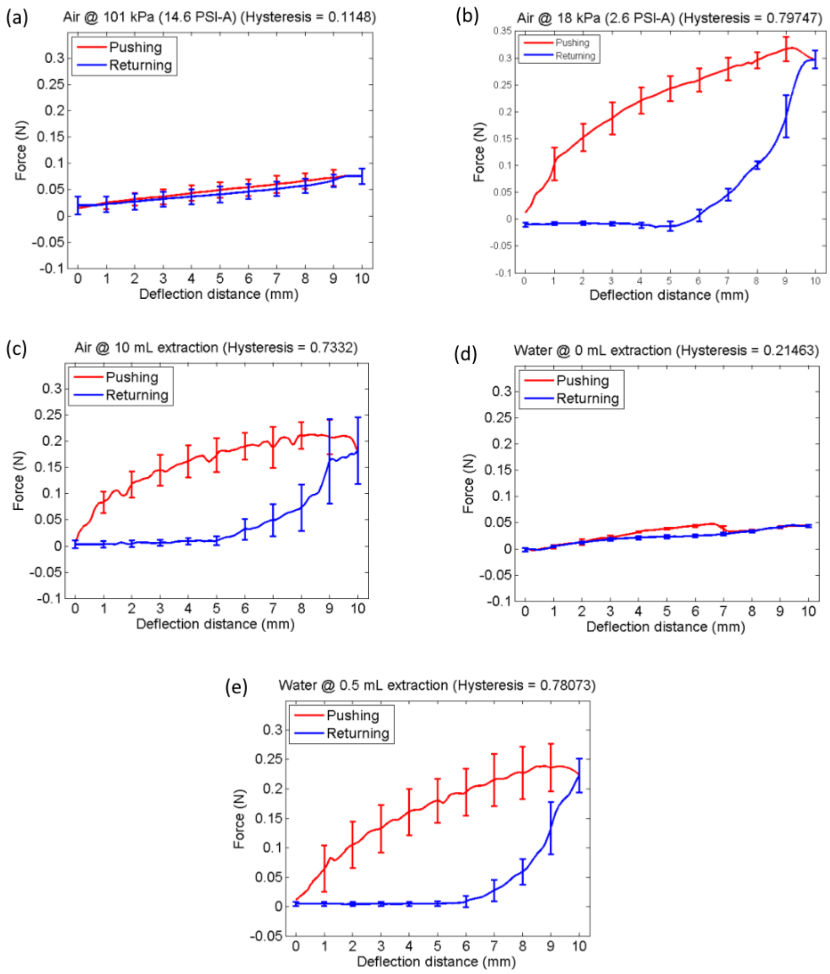

Figure 3.3: [Jiang et al., 2013] experiments to compare hydraulic jamming approach with deaired water to pneumatic jamming: (a) Air control stiffness under no additional pressure; (b) Result of continuous vacuum draw with pressure of 18 kPa in pneumatic system; (c) stiffness result of 10 mL air evacuation via syringe; (d) Water control stiffness under no additional pressure; (e) Result of 0.5 mL water evacuation using a syringe. The hysteresis H calculates with $H = \frac{A_{push} - A_{return}}{A_{push}}$

3.4 Implementation

When it comes to the type of device, contrary to what one may believe, handheld VR devices are commonly more convenient and provide a more pleasant VR-Experience than wearable gloves. As concluded by [WANG et al., 2019], handheld haptic devices strike compared to gloves since they can just be picked up and instantly be used, while gloves usually have to be put on first. Additionally, handheld devices such as controllers can quickly adapt to different hand sizes, an issue that gloves face. As a result, controllers remain dominant in the market (e.g., Oculus Rift and HTC Vive).

As for jamming, according to [JIANG et al., 2012], affected by the material, size, and shape of the granules and their embracing membrane, the overall spectrum of stiffness levels and the ability to deform will vary. Some granules may only allow a slight change in stiffness when jammed but enable a very rigid jammed state. Contrary to that, in extreme cases, liquids work very well for simulating softness but will probably lack the possibility of simulating rock-hard objects, even when jammed. Also influencing the stiffness levels is the shape and volume of granules relative to their membrane. Essential for maximising the rigidity is having the highest possible total volume of all granules compared to its membrane volume.

The ultimate goal for realising a highly immersive virtual haptic perception is to have a large jamming spectrum, ranging from rock-hard firmness to almost fluid-like consistency. Additionally, we want to keep the device as lightweight as possible and preferably have the device be compact.

To examine the very problem, references to various studies will follow.

3.4.1 Granular, Layer and Fibre Jamming

As stated before, jamming appears in three different ways: granular, layer, and fibre jamming. To discern the most suitable type of jamming for handheld haptic and jamming devices, we got to look at each of their properties and evaluate what suits best for our case.

Remarkably, only Layer jamming is limited in shape. Layer jamming is bound by a planar shape, but there is almost no restraint for fibre and granular jamming regarding their size and shape. To uphold a great user experience, handheld devices should be lightweight to prevent burdens on the user over time. In contrast to granular jamming, fibre and layer jamming tend to be lighter and require less volume. Granular jamming, on the other hand, allows for a broader range of stiffness levels. It is the only jamming method that can function as fluids, in the manner of [FITZGERALD et al., 2020].

This paper at hand focuses on granular jamming. Granular jamming is the most ubiquitous jamming method hitherto, considering the increased stiffness scope and the least bondage of the three approaches to specific geometries. Fibre and layer jamming only fell under research in recent years. Hence the quantity of their information is relatively low compared to granular jamming, all the more reason to further study the other types of jamming. The newest of them, fibre jamming, seems to be very promising in the field of jamming.

3.4.2 Granular Material

There is no limit to granules that work for jamming. [Fitzgerald et al., 2020] compares materials and designs of different jamming actuation of soft robotics. According to them, granules are distinguished between artificial and natural. The common usage of ground coffee is an excellent instance of natural grains for jamming. Coffee powder and rice are sometimes used as well, to name a few. Surprisingly, as it can be seen in Figure 3.4 (left), natural grains are more frequently used than artificial granules like glass spheres, rubber cubes, and others. As for layer jamming, paper, sandpaper, and polyethylene terephthalate are, to this date, commonly employed (see Figure 3.4 (right)). Some fibre materials fibre jamming uses are waxed cotton, silicone, nylon, and leather.

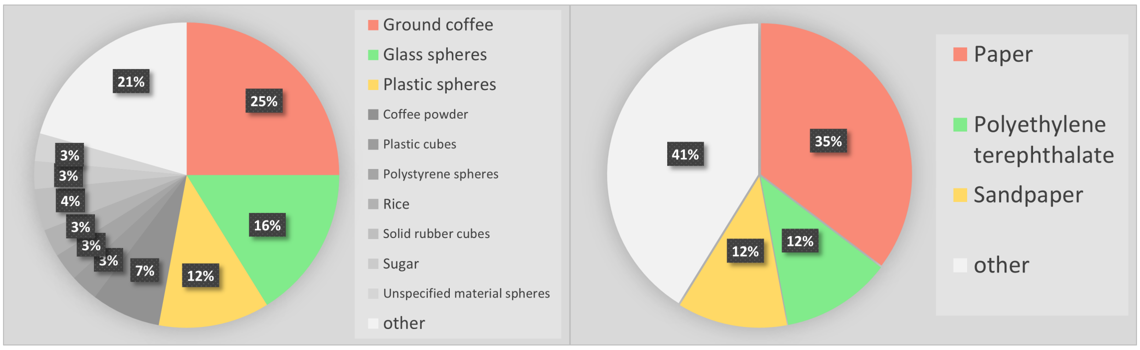

Figure 3.4: Frequency of grain materials (left) and sheet materials (right) for granular and layer jamming of various studies found by [Fitzgerald et al., 2020]

Nevertheless, some materials work better for jamming than others. In [Jiang et al., 2012], it is shown for granular jamming that solid plastic granules covered in a 0.5 mm layer of polyurethane rubber exhibit a more extensive force range over purely rubber granules and also an improvement of the hysteresis and variability over purely plastic granules. [Cavallo et al., 2019] tested commonly used natural granules in jamming. They compare the stiffness of pepper, salt, sugar, and ground coffee when compressed in a single-chambered shore 30 silicone membrane. Salt achieved the highest stiffness variation and the most extensive stiffness range, followed by coffee. Pepper provided a similar range to coffee. Unlike its soft state, sugar's deviation under compression was the smallest. Under a high-resolution microscope, they attributed coffee's high stiffness variation to its surface roughness and irregular shape. It is concluded that the grain geometry and surface roughness influence the stiffness in a jamming system.

[Jiang et al., 2012] further examines the effect of the shape of granules on the outcome variability and overall stiffness. As reported by them, 4mm cube granules are more suitable for robotic systems than spheres due to their linearity and repeatability, although cubes lose some stiffness variability compared to sphere-shaped granules. As for the sense of touch in virtual reality, a higher maximum stiffness will most likely increase the immersive feeling, but consistency is always something that has to be kept in mind. Since many factors influence both maximum stiffness and variability, that is something to conduct further research on by actually testing and comparing different granules in the same haptic device that utilizes jamming.

[Fitzgerald et al., 2020] evaluated how a change in grain size influences the bending stiffness of actuators in soft robotics by comparing multiple studies. Modifying the granule size alters achievable stiffness levels. However, heterogeneous outcomes of similar tests suggest that possible stiffness does not solely rely on granule size but rather depends on the granule's relation to the volume of their enclosing membrane.

On that note, [Jiang et al., 2012] conducted an experiment where the rigidity of 4mm, 6mm, and 8mm diameter plastic sphere granules and smaller plastic cube granules, down to 1.5mm in diameter, were examined under different pressures.

According to them, an important factor to maximize is the volume fraction ϕ with the equation:

$$\phi = \frac{V_{granules}}{V_{total}} \tag{3.4}$$

[Jiang et al., 2012] claim that an increase in the volume fraction ϕ results in better stiffness ranges.

The experiments put stress on the effect of different grain sizes and shapes. The 4 mm plastic spheres turned out to have the highest and most consistent stiffness of all tested plastic sphere sizes. Remarkably, grain sizes below 4 mm show no significant difference in achievable stiffness and variance.

Overall, the examined works conclude that the smaller the grains, the more traction between individual granules and the membrane occurs due to a larger inner membrane surface area to volume ratio, resulting in a larger achievable stiffness spectrum (as shown in Figure 3.5 (a)). However, that does not provide a low variance between stiffness outcomes nor results in a low hysteresis.

3.4.3 Membrane

The membrane is made out of elastomers. Primarily latex or silicone is used. Even though latex is more economically friendly and tends to be more flexible, silicone is generally preferred in medical instances due to similar properties and precautions against allergic reactions.

Through experiments of [Fitzgerald et al., 2020], it was discovered that the membrane rigidity primarily influences the stiffness of an unjammed cell and that the membrane material also has a significant effect on the bending stiffness of a granular jamming actuator.

In an attempt to examine the relation of stiffness to membrane size and thickness, researchers conducted experiments. [Li et al., 2017] observed that a larger membrane thickness correlates to an increased maximum stiffness (see Figure 3.5 (b)). In accord with them, the reason for that is the actuator's ability to expand more at the same pressure with a smaller wall thickness. As a result, a larger stiffness is achieved because a larger pressure is applied to the particles.

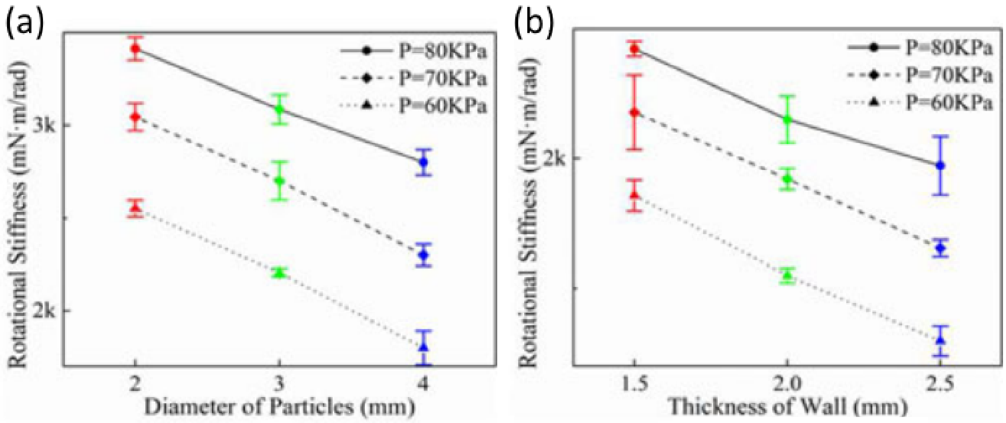

Figure 3.5: Influence on stiffness under different pressures with (a) different grain sizes, (b) different membrane thicknesses. Credit: [Li et al., 2017]

Through an experiment conducted by [Jiang et al., 2014], where half-spheres of the same size as the granules were attached to the inner surface of a membrane, it was concluded that membranes should be soft and flexible to maintain good contact with the granules. The conclusion is based on the vast improvement in hysteresis and linearity, even though the overall system did not improve significantly.

As stated above, the properties of different membrane materials play a notable, if not the most, crucial role in affecting the stiffness, hysteresis, and stiffness variance of jamming. Latex as the go-to surgical membrane material was compared with vinyl and nitrile as latex-free substitutes, a mixture of both substitutes vitrile with higher strength and flexibility, and polythene which is commonly used for food packaging [Jiang et al., 2014]. The joint of the experiment was a 15 mm diameter cylinder with a length of 40 mm. 4 mm glass spheres filled the joint. The elasticity was examined for each material with no additional pressure or granules. The stiffness was measured in Young's modulus

$$E = \frac{\sigma}{\epsilon} \tag{3.5}$$

where σ is applied stress in force F per area A

$$\sigma = \frac{F}{A} \tag{3.6}$$

and ϵ the normal (axial) strain in

$$\text{strain } \epsilon = \frac{\text{stretch } \delta}{\text{original length } L}. \tag{3.7}$$

The membrane-only tests showed nearly identical, almost linear behaviour for latex, vinyl, vitrile, and nitrile. All named membranes also exhibited small hysteresis, except nitrile with a slightly larger one. Polythene attained ten times greater stress and thus a corresponding larger E value than the other membranes. [Jiang et al., 2014] contributes the large polythene hysteresis to permanent deformation caused by stretching the membrane.

The stiffness property of the individual materials using jamming was compared for three applications: bending, stretching, and compressing. Each experiment was conducted at three different pressure levels: 101 kPa (15 PSI-A), 55 kPa (7.5 PSI-A), and 10 kPa (1.5 PSI-A), regulated by an oil-based vacuum pump.

Except for polythene, all membranes exhibited a similar value under atmospheric pressure in the tensile test as in the membrane-only tests. It shows that the granules are mostly inconsequential for the tensile strength in the soft state. Towards vacuum, latex, vitrile, and nitrile increased by 100% up to 200% in E value while polythene only increased by 50% and vinyl remained unchanged (see Figure 3.6(b)). Although two membranes may display similar properties in a soft state, their characteristics change when applying a vacuum. This was validated through pairwise Mann-Whitney U tests on the peak stresses of all materials at 101 kPa internal pressure. Nitrile and vinyl values were very close to one another, but when jammed, their stresses differentiate.

The compression test exhibit a significant variation of hysteresis of each membrane between jammed and unjammed pressures. Additionally, it was found that a higher hysteresis with higher internal pressure attributes to the membrane's inability to return to its initial shape when returning pressure. A permanent deformation characterizes vitrile and polythene in the joint under 20% compressive strain. The supposed cause is the restructuring of the granules. In this test, polythene was not vastly stiffer than the other four materials at vacuum. Vinyl exhibited the largest stiffness range (diagram in Figure 3.6(c)).

Bending does not necessarily apply strain to the joint. It primarily causes deformation on the horizontal axis. Hence, the in beforehand presented formula for

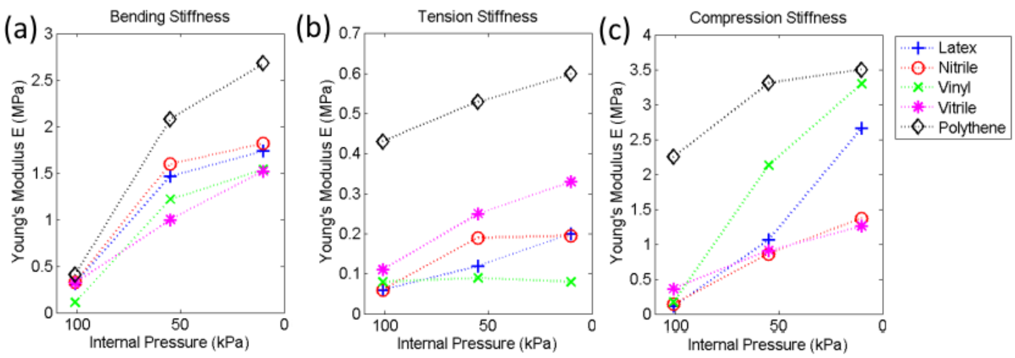

Figure 3.6: Relationship between vacuum pressure and stiffness for (a) bending, (b) tension, (c) compression. Credit: [Jiang et al., 2014].

Young's modulus E becomes meaningless for the bending test and needs to be adjusted [JIANG et al., 2014]:
The joint was fixed at one end, and force was applied to the jamming joint's tip. M is the total bending moment for the joint and is defined as:

$$|M| = |L||F_{ext}| \tag{3.8}$$

with L being the length of the joint and F_{ext} the externally horizontally applied force onto the tip by a motorized linear rail. The moment at a single point along the joint is characterized by:

$$M = F_{ext}(L - d) \tag{3.9}$$

where d is the distance from the fixed end. The bending behavior can be described by the following equation:

$$y(d) = \frac{F_{ext} d^2 (3L - d)}{6EI} \tag{3.10}$$

$y(d)$ is the perpendicular displacement of the joint along distance d. I as the area moment of inertia calculates as follows:

$$I = \frac{\pi r^4}{4} \tag{3.11}$$

with r as the radius of the joint. By rearranging Equation 3.8, the bending stiffness can be measured in Young's modulus E with:

$$E = \frac{4 F_{ext} L^3}{3\pi y(L) r^4} \tag{3.12}$$

Figure 3.6(a) visualizes the value of Young's modulus for each membrane material. All membranes behave similarly under different pressures. Polythene stands out slightly with having the largest E values. According to [JIANG et al., 2014], this shows the correlation of Young's modulus value to the elasticity and stiffness of the joint as a whole.

Overall, latex and nitrile ended up as superior materials. Mainly latex provides a low variance in E values relative to other materials between the different tests. Vinyl and vitrile are inconsistent compared to latex. In some tests, they attain better values, and in others, worse. Polythene gained the highest E values in all tests, thus being a suitable material for applications where high stiffness is desired. However, it shows that polythene does not provide the best stiffness ranges and has a relatively rigid soft state compared to the other testes materials.

3.4.4 User Input

A person can perceive multiple stiffness levels with the same object through jamming. Up to this point, that is just a one-way system, but we want to be able to interact with and manipulate objects of virtual environments in real-time and receive proper feedback. [Follmer et al., 2012] present two methods that enable jamming systems to sense user input.

One proposed way is to have two electrodes, one attached to the jamming surface and one at the fix-point of the jamming cell. One of the electrodes transmits a signal to the other one. In the showcased design, a 9×9 receiving electrode grid of conductive fabric strips was placed upon the jamming surface, on its fixed back 9×9 transmitting electrodes of copper tape strips (visible in Figure 3.7 (left)). On top of the receiving electrodes, a grounded conductive fabric is attached to protect the electrode's transmission from the user. An analogue multiplexer connects the receiver electrodes to the amplifier circuit and analogue-to-digital converter. Data transmits over USB or Bluetooth with a 30 Hz transmission rate. A possible outcome received by the system over the user input looks like Figure 3.7 (right). The only issue here is that, in a completely jammed state, pressing into the jamming area requires great force or is impossible. Thus, it requires another sort of touch tracking or hand closing for the system to gain initial grabbing feedback. In the case of handheld devices, a possible way to resolve the issue is by having a surface that can sense touch, similar to the touch-sensitive buttons of Oculus Rift's controllers. One possibility is to have a flexible touch switch foil on top of the jamming surface.

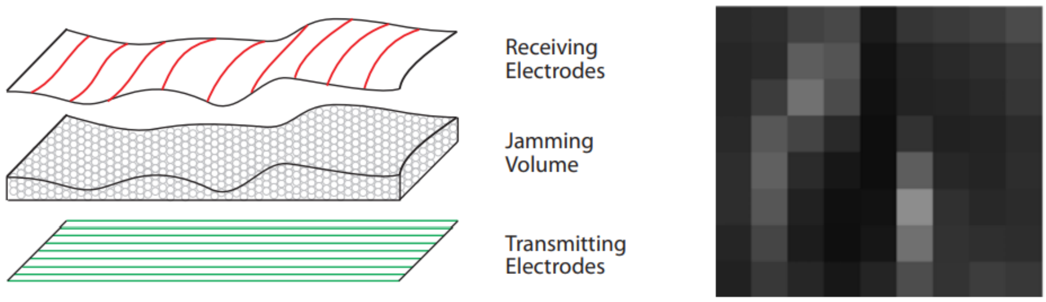

Figure 3.7: Left) The jamming shape is computed by the value received at the receiving electrodes transmitted by the transmitting electrodes. Right) Raw depth map example in a 9×9 capacitive shape sensing system. Credit: [Follmer et al., 2012].

The other presented method for jamming systems to sense user input is to have a rear-mounted camera pick up structured light thrown by an infrared projector (see Figure 3.8). Required for it to work are transparent liquid and clear granules that have matching refractive indices to suppress refraction, which would else result in opaqueness and hinder the light. In addition, through a thin, semi-transparent skin made of silicone, the system can perceive the user's touch due to the camera capturing reflections from fingers as they make contact. It should be noted that this approach is limited to hydraulic jamming.

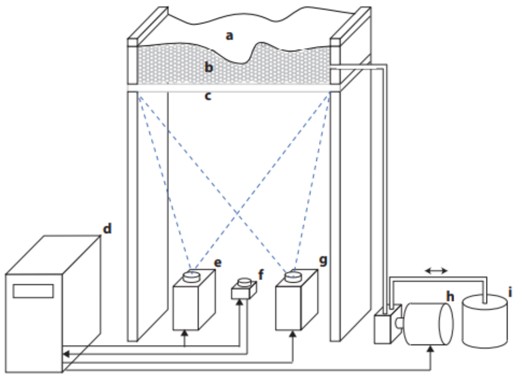

Figure 3.8: Structured Light Depth Sensing System with Index-Matched Jamming: (a) Silicone Membrane, (b) Pyrex glass beads and oil, (c) acrylic plate, (d) computer, (e) structured light IR projector, (f) IR camera, (g) graphics projector, (h) hydraulic pump, (i) reservoir. Credit: [Follmer et al., 2012].

4 Conclusions and Future Research

This paper presents the state of the art of haptic jamming. Haptic jamming functions as the first step toward implementing the perception of object stiffness in virtual environments for handheld haptic devices and contributes to the eventual creation of multi-modal systems for virtual reality. By referring to various studies, an overview of what needs to be considered when designing such devices was given. To obtain the most immersive haptic experience, a haptic device that supports stiffness perception should be able to simulate a large spectrum of rigidity levels. High maximum stiffness for hard materials like metals, rocks, and similar needs to be obtainable and low stiffness levels, possibly up to almost liquid-like consistency, are desired. To enable predictability and controllability, as well as to have the jamming system produce consistent outputs, a low hysteresis should be aimed for. Furthermore, to deliver a pleasant encounter, the device's weight should remain as light as possible and not be too voluminous. Obviously, not all stated properties are easily achieved at once. Many of their effects contradict each other. Throughout this paper, it has become clear that many factors influence jamming behaviour. In the following, I will summarise what can be done to maximize each desired characteristic of an optimal haptic jamming device.

It was shown that the size of granules and the grain's shape and surface roughness influence the stiffness outcome. Frankly, smaller granules lead to more traction between individual grains and the membrane, which increases the achievable stiffness scope. Grain sizes under 4 mm do not significantly enlarge the effect. Coffee's high stiffness variation is regarded to ground coffee's rough outside and its divergent geometry. On the flip side, the total volume limits the jamming stiffness. Small volumes struggle to obtain low rigidity stages and lack in stiffness range. Derived from Young's modulus, the smaller objects are, the harder it is to manipulate them. Hence there is a limit to how compact a jamming cell can be and yet achieve a good stiffness spectrum. The most significant effect of properties in jamming seems to be owned by the membrane. It was shown that the enclosing membrane should be rather slim since that enhances the maximum stiffness. A more flexible and soft membrane correlates to an improved hysteresis and linearity. In comparing commonly used membrane materials, latex turned out to be the most effective and reliant material.

Hydraulic jamming systems were compared to the standard pump-based pneumatic jamming systems. Since liquids are incompressible, hydraulic systems have higher efficiency, can be stiffer, quieter, and can withstand more stress as well as load than pneumatic systems. In contrast, the cylinders used to extract the liquid to jam the contraption and the liquid itself add considerable weight to the device. Leaks in the system render it completely unusable since the influx of air causes the device to lose the ability to stiffen.

Future research consists of creating handheld devices and conducting experiments and practical tests within its implementation. Promising fields for further research are hydraulic jamming systems due to their many advantages over pneumatic systems. Similarly promising seems fibre jamming as an alternative to granular jamming. Thus it is worthy of further thorough study.

For the long-term vision to design highly immersive multi-modal haptic devices, research in all the different haptic perception areas is required. Temperature and friction perception, roughness sensing, as well as feeling shapes are, likewise to softness simulation, not exhaustively explored. Electrostatic effects might be a starting point for roughness sensing to look into. Jamming also seems very promising to reenact object's geometries which was out of scope for this paper.

Bibliography

[Bianchi et al., 2016] Bianchi, Matteo, E. Battaglia, M. Poggiani, S. Ciotti and A. Bicchi (2016). *A Wearable Fabric-based display for haptic multi-cue delivery*. In *2016 IEEE Haptics Symposium (HAPTICS)*, pp. 277–283.

[Brown et al., 2010] Brown, Eric, N. Rodenberg, J. Amend, A. Mozeika, E. Steltz, M. R. Zakin, H. Lipson and H. M. Jaeger (2010). *Universal robotic gripper based on the jamming of granular material*. Proceedings of the National Academy of Sciences, 107(44):18809–18814.

[Cavallo et al., 2019] Cavallo, Aida, M. Brancadoro, S. Tognarelli and A. Menciassi (2019). *A Soft Retraction System for Surgery Based on Ferromagnetic Materials and Granular Jamming*. Soft Robotics, 6(2):161–173. PMID: 30407125.

[Fitzgerald et al., 2020] Fitzgerald, Seth G., G. W. Delaney and D. Howard (2020). *A Review of Jamming Actuation in Soft Robotics*. Actuators, 9(4).

[Follmer et al., 2012] Follmer, Sean, D. Leithinger, A. Olwal, N. Cheng and H. Ishii (2012). *Jamming User Interfaces: Programmable Particle Stiffness and Sensing for Malleable and Shape-Changing Devices*, p. 519–528. Association for Computing Machinery, New York, NY, USA.

[Garbe, 2020] Garbe, Julius (2020). *Hysteresis For Dummies – Why history matters*.

[Jiang et al., 2013] Jiang, Allen, T. Aste, P. Dasgupta, K. Althoefer and T. Nanayakkara (2013). *Granular Jamming With Hydraulic Control*.

[Jiang et al., 2014] Jiang, Allen, T. Ranzani, G. Gerboni, L. Lekstutyte, K. Althoefer, P. Dasgupta and T. Nanayakkara (2014). *Robotic Granular Jamming: Does the Membrane Matter?*. Soft Robotics, 1(3):192–201.

[Jiang et al., 2012] Jiang, Allen, G. Xynogalas, P. Dasgupta, K. Althoefer and T. Nanayakkara (2012). *Design of a variable stiffness flexible manipulator with composite granular jamming and membrane coupling*. In *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 2922–2927.

[Kim et al., 2013] Kim, Yong-Jae, S. Cheng, S. Kim and K. Iagnemma (2013). *A Novel Layer Jamming Mechanism With Tunable Stiffness Capability for Minimally Invasive Surgery*. IEEE Transactions on Robotics, 29(4):1031–1042.

[Li et al., 2017] Li, Yingtian, Y. Chen, Y. Yang and Y. Wei (2017). *Passive Particle Jamming and Its Stiffening of Soft Robotic Grippers*. IEEE Transactions on Robotics, 33(2):446–455.

[Schmidt, 1978] Schmidt, I. (1978). *Flexible moulding jaws for grippers*.

[Simon et al., 2014] Simon, Timothy M., R. T. Smith and B. H. Thomas (2014). *Wearable Jamming Mitten for Virtual Environment Haptics*. In *Proceedings of the 2014 ACM International Symposium on Wearable Computers*, ISWC '14, p. 67–70, New York, NY, USA. Association for Computing Machinery.

[Stanley and Okamura, 2017] Stanley, Andrew A. and A. M. Okamura (2017). *Deformable Model-Based Methods for Shape Control of a Haptic Jamming Surface*. IEEE Transactions on Visualization and Computer Graphics, 23(2):1029–1041.

[WANG et al., 2019] WANG, Dangxiao, Y. GUO, S. LIU, Y. ZHANG, W. XU and J. XIAO (2019). *Haptic display for virtual reality: progress and challenges*. Virtual Reality Intelligent Hardware, 1(2):136–162.

[Zubrycki and Granosik, 2015] Zubrycki, Igor and G. Granosik (2015). *Novel haptic glove-based interface using jamming principle*. In *2015 10th International Workshop on Robot Motion and Control (RoMoCo)*, pp. 46–51.