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An Investigation of the Interrelationship between Physical Stiffness and Perceived Roughness

Theodoros Georgiou, Alistair D. N. Edwards
The University of York
Department of Computer Science, Deramore Lane, York. UK, YO10 5GH
tg633@york.ac.uk; alistair.edwards@york.ac.uk

Abstract **-** Research in the area of haptics and how we perceive the sensations that come from haptic interaction started almost a century ago, yet there is little fundamental knowledge as to how and whether a change in the physical values of one characteristic can alter the perception of another. The increasing availability of haptic interaction through the development of force-feedback devices opened new possibilities in interaction. It allowed for accurate real time change of physical attributes on virtual objects in order to test the haptic perception changes to the human user. An experiment was carried out to ascertain whether a change in the stiffness value would have a noticeable effect on the perceived roughness of a virtual object. Participants were presented with a textured surface and were asked to estimate how rough it felt compared to a standard. What the participants did not know was that the simulated texture on both surfaces remained constant and the only physical attribute changing in every trial was the comparison object's surface stiffness. The results showed that there is a strong relationship between physical stiffness and perceived roughness that can be accurately described by a power function. Furthermore, the roughness magnitude estimations showed an increase with increasing stiffness values. The conclusion is that there are relationships between these parameters, but that further work is required to validate those relationships.

Keywords**:** Virtual haptic perception, Force-feedback, Roughness, Stiffness.

1. Introduction

Textural information can be obtained by visually inspecting an object (Heller, 1989) or by listening to the sounds produced during exploration (Lederman, 1979). However, much finer and more complex textural information can be obtained through touch. During haptic exploration of a surface, we may perceive the surface as being rough, like sandpaper, or smooth, like glass; the surface may also vary among other sensory continua, such as hardness (e.g. stone) vs. softness (e.g. silk), stickiness (e.g. tape) vs. slipperiness (e.g. soap). Also, whether a texture is thermally insulating (e.g., wood) or thermally conductive (like metal) contributes to the textural percept (Hollins and Risner, 2000), (Bensmaïa and Hollins, 2005).

Haptic virtual environments are to haptic perception research as computer graphics are to vision research. They allow the investigation of haptic perception, the techniques used for exploration and any related phenomena in novel ways that often include the creation of objects that do not exist naturally in the real world. Haptic virtual environments offer great flexibility over the control of mechanical signals, allowing the perception of these stimuli to be measured in a quantitative way; something that is extremely difficult to measure otherwise.

This close relationship between the research on haptic perception and haptic technology is a source of constant advancements in both fields. Evidently, human perception research greatly benefits from haptic technology and, equally, haptic technology benefits greatly from research on human haptic perception. Therefore, with all the current and future advancements in both fields, we are offered potentially with very important opportunities for understanding haptic perception. This may even highlight the profound importance of some underrated haptic phenomena (Robles-De-La-Torre, 2006) like somesthesis[1] and proprioception[2].

By better understanding how we perceive touch in order to determine the characteristics of a physical object we are touching, haptic technology can be used to provide enhanced interaction experience to the user. This may be for leisure (force feedback in video games) or for simulating reality and real-life situations (virtual training of doctors and surgeons, and machine operators). Also, haptic feedback has been recently used on a prosthetic arm to provide a patient who had lost his arm with the ability to touch and feel his environment again. With the new prosthetic arm the patient could judge the stiffness and shape of different objects by exploiting different characteristics of the elicited sensations in real time (Raspopovic, et al., 2014). This is a significant step forward, towards directly improving a person's quality of life with research on human haptic perception.

On the other hand, while going over the relevant literature, it is apparent that the majority of research to date concentrates on how changing one physical attribute affects its relative perception (e.g. physical stiffness with how "hard" it feels, or inter-element spacing with how "rough" it feels). Not much research has been done on how the physical change of one attribute affects the perception of another (e.g. the effect of physical stiffness on perceived roughness) in a way similar to intermodal interactions, where different senses work together and influence the perception of each other.

The work described herein investigated how physical stiffness of a virtual object affects the perception of its roughness. The need of this investigation is inspired by a gap identified in the literature, indicating that very little has been done in the past on how haptic attributes of one object (e.g. stiffness and surface texture) affect the perception of each other.

2. Method

This experiment was designed to investigate how changing the physical stiffness of an object affects its perceived roughness. The design of this experiment was based on the method of magnitude estimation as defined by Stevens (1971). With this method, a group of participants were asked to feel a number of virtual surfaces using the Geomagic Touch force feedback device (FFD)[3]. This device was formerly known as the Phantom Omni by SensAble™ and is shown in Figure 1. Participants were asked to assign numbers to them representing how rough they felt. The participants at that stage did not know that the physical attributes that make a surface feel "rough" were kept constant and only the physical stiffness of the surfaces was changing. The results were then analysed and a conclusion of how the perception of roughness changes in relation to the surface's physical stiffness was then drawn.

2. 1. Participants

Thirty consenting, healthy adults, students and staff from the University of York (mean age: 28 years, range 21-49 years, 16 males, 14 females), participated in this experiment. Twenty-eight participants were right-handed and 2 left-handed. None reported any cutaneous or motor impairment.

2. 2. Materials

For the purpose of this experiment a force feedback device was used. The force feedback device chosen for the purpose of this study was a Geomagic Touch. This is a haptic FFD device, which makes it possible for users to touch and manipulate virtual objects. It has six degrees of freedom with positional sensing and uses an array of motor actuators attached on a mechanical, robotic arm to replicate haptic properties of virtual objects in the real world (SensAble Technologies Inc., 2008).

The Omni works in a virtual space, which measures approximately 160mm width x 120mm height x 70 mm depth (6.4 x 4.8x 2.8 in). This makes it very compact and capable of working in space-limited

[1] Somesthesis refers to the various sensory systems in the skin and other bodily tissues responsible for the sense of touch (e.g. pressure, warmth and coldness, pain, itch)

[2] Proprioception refers to the sense, which allows us to know where our limbs are in relation to our body.

[3] http://geomagic.com/en/products/phantom-omni/overview

environments such as a lab workbench. The device can generate a force of approximately 3.3N (0.75 lbf) (SensAble Technologies Inc., 2008).

Fig. 1. The Geomagic Touch force feedback device.

The machine used for controlling the FFD was a computer system with an Intel® Pentium® 4 Core 2 Duo processor at 3.00 GHz and 4GB of RAM. It also had a Radeon™ graphics card, capable of supporting two screens. The use of two screens was essential to parts of the experiment where the facilitator had to monitor values, which the participants should not see.

The lab machine used was running a 64bit version of Microsoft Windows 7 operating system and the code used for controlling the Phantom Omni was written and compiled in Microsoft Visual Studio 2010 with the OpenHaptics (Academic Edition) software development toolkit integrated into it.

There are two main components of the graphical interface in the system, namely: the two flat surfaces onto which the haptic attributes are attached, and the haptic cursor, which visually represents the end-effector of the FFD (see Fig. **2**).

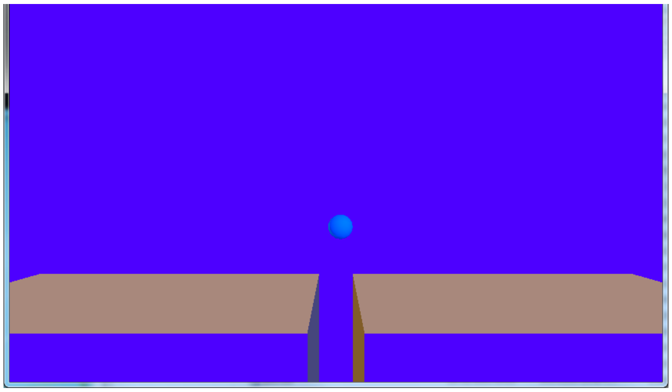

Fig. 2. Two virtual flat surfaces as used for the two experiments.

The visual component of all of the surfaces (including the cursor), were drawn using OpenGL graphics. No visible changes (such as surface deformation) were implemented on the surfaces when haptic values were changing during the experiment, keeping the visual and haptic component of the virtual environment parallel (one drawn on top of the other) but independent from each other.

The two surfaces were rendered as horizontal planes, at the same height with a small gap between them**.** This gap prevented the participants from exploring both surfaces with one long motion.

A sphere was created to function as the visual representation of the cursor using OpenGL graphics. The x, y and z coordinates of the FFD were attached to this sphere and moved accordingly to the FFD's end effector movements. A blue sphere of a finite diameter represented the visual component of the cursor so that participants could see the cursor and navigate through the three-dimensional space more easily.

The virtual haptic cursor was implemented on top of the visual cursor and had an infinitely small diameter. Since this experiment was not intended to investigate the effect of the point-of-contact area or diameter to the perception of hardness and roughness, implementing a cursor with a set diameter would only make this program more computationally "heavy". This haptic cursor was implemented to be in the centre of the sphere acting as the visual cursor.

There is a number of ways the surface texture can be altered in the haptic virtual environment. A virtual object for example can be rendered having a virtual "physical" micro-texture, with raised elements, simulating texture in a similar way as in the real world. The perception for roughness can then be altered by changing different attributes of that micro-texture (i.e. altering groove-land width, element spacing etc.).

Another way of simulating surface texture for psychophysical experiments examining roughness perception is by using a friction model (Unger, 2008). This project simulated surface texture using 'stick-slip' action.

Stick-slip can be described as surfaces alternating between sticking to each other and sliding over each other, with a corresponding change in the force of friction. Typically, the static friction coefficient (a heuristic number) between two surfaces is larger than the dynamic friction coefficient. If an applied force is large enough to overcome the static friction, then the reduction of the friction to the dynamic friction can cause a sudden jump in the velocity of the movement. Fig. **3** describes how stick-slip works.

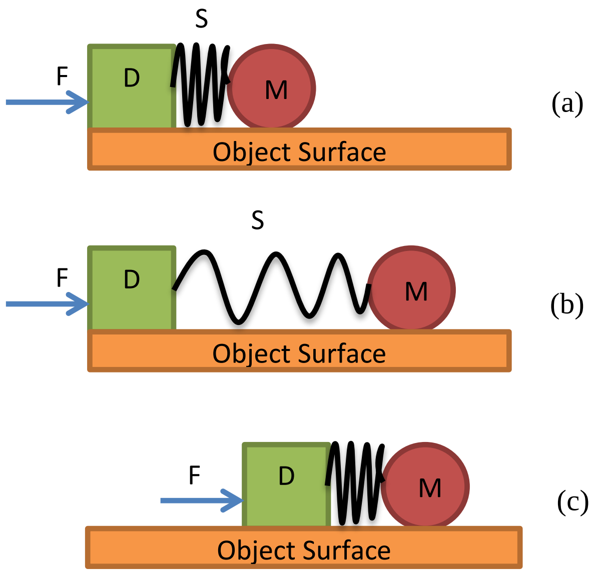

Fig. 3 Stick slip representation.

F is the force applied and D is a drive system used for controlling a virtual spring. The user supplies this force during the interaction. S is the elasticity in the system, and M is the load (cursor in our case, with a weight equal to the force the user applies perpendicular to the object's surface) that is lying on the object surface and is being pushed horizontally. When the drive system is started (stage (a)), the spring S is loaded and its pushing force against load M increases until the static friction coefficient between the load M and the surface in contact is no longer able to hold the load any more. The load starts sliding and the friction coefficient decreases from its static value to its dynamic value (and from "stick" to "slip"). At this moment the spring can give more power and accelerates M (b). During M's movement, the force of the spring decreases, until it is insufficient to overcome the dynamic friction. From this point, M decelerates to a stop. The drive system however continues, and the spring is loaded again, going back to stage (a), ready to repeat the process.

This constant sticking and slipping, causes the user to perceive this motion as being equivalent to the motion over a textured surface, giving the perception of a "rough" surface.

Simulating a "rough" surface this way has a number of advantages in the context of this experiment. First of all it is much faster to produce a number of different surfaces, all varying in their roughness level. The alternative would be to describe each surface with an algorithm similar to Kornbrot et al. (2007) or using 3D modelling software to produce a different wireframe mesh surface for every object used and alter each individual surface micro-texture. In addition, as seen from the literature, the probe size plays a significant role in how roughness is perceived (Unger et al, 2011), but simulating "roughness" on a surface using static friction, enables the use of probe with an infinitely small diameter. Lastly, the OpenHaptics Toolkit API (SensAble Technologies, 2008) provides a method that enables the programmer to dynamically change an object's haptic parameters of "stiffness", "static" and "dynamic friction". Thus this was a tried-and-tested method to assign these parameters on the haptic objects.

2. 5. Procedure

Participants were asked to sit in front of the Geomagic Touch, facing the device and the computer screen at a 90-degree angle. Then they were asked to make themselves comfortable, adjusting the distance of the FFD from them to a point they found it most comfortable. At this point the participants thought that the experiment would be about manipulating the haptic texture of the virtual objects and measuring their perception of "roughness". Stiffness was never mentioned to them until the debriefing session at the end.

Before starting the experiment, each participant was given a brief explanation, of what is meant by "roughness" in the context of this experiment. This was done by saying to the participant that "*for example, if we feel the rug of the room with a probe, it will feel rougher than when feeling the top of the desk with the same probe*" while demonstrating with the back end of a pen. In some cases this definition and demonstration was carried out in Greek, describing "rough" as "τραχύ" (trachý). After the definition of what is meant by "rough" was clarified and the participants confirmed that they understood that definition and had no further questions, instructions as to what they had to do were given.

Participants were informed that they would be presented with two flat surfaces on the computer monitor in front of them, which they could feel using the FFD. As mentioned above, this was a magnitude estimation experiment. The procedure followed was identical to the one proposed by Stevens' paper (Stevens & Harris, 1962). Both stimuli were presented simultaneously to the participant and they were asked to say how rough they felt by assigning numbers to them. They were informed that the surface to the left was to act as the standard stimulus and therefore would remain unchanged throughout the experiment. The first thing they were asked to do was assign a number (modulus) to this standard stimulus. Stevens notes that allowing the participants nominate a number for the standard has no difference from giving a number at the beginning during the briefing, but rather he claims that in his experience it is usually better to let the participants designate the standard (Stevens, 1971). The only limitation given to the participants was that the number they would nominate had to be more than zero. Then their task in each trial was to assign numbers to the comparison (right) surface proportional to their subjective impression of roughness. They could use whatever numbers seem appropriate (fractions, decimals, or whole numbers) as long as they were not zero and not negative. For example, if they assigned 10 as the modulus to the standard at the beginning, and a surface felt 3 times as rough as the standard they had to say 30; if it felt half as rough they had to say 5; if they thought it was one fifth as rough, they had to say 2, etc. Participants were also informed not to worry about being consistent, but to try to give the appropriate number to each surface regardless of what they might have called some a previous surface.

Two repetitions per set per participant were performed, each in a different random order. As Stevens suggests, "*a good schedule should provide for one judgement, or at most two judgements per stimulus per subject (participant)*" (Stevens, 1971).

After the last trial, each participant was debriefed and any questions they might have were answered. At this point the deception – that it was stiffness that had been manipulated – was revealed.

3. Results

Once a participant finished, the mean of the magnitude estimation ratios of the two repetitions per pair was calculated. Stevens then suggests using the geometric mean (GM) when calculating the average of magnitude estimation for every pair across all participants (Stevens, 1971). The use of a geometric mean instead of an arithmetic mean is necessary since every participant was free to use any value for the modulus they wanted, potentially having different numeric ranges for every participant. Therefore, the slope determined by the geometric mean is not affected by the fact that every participant was free to use a different unit for the modulus.

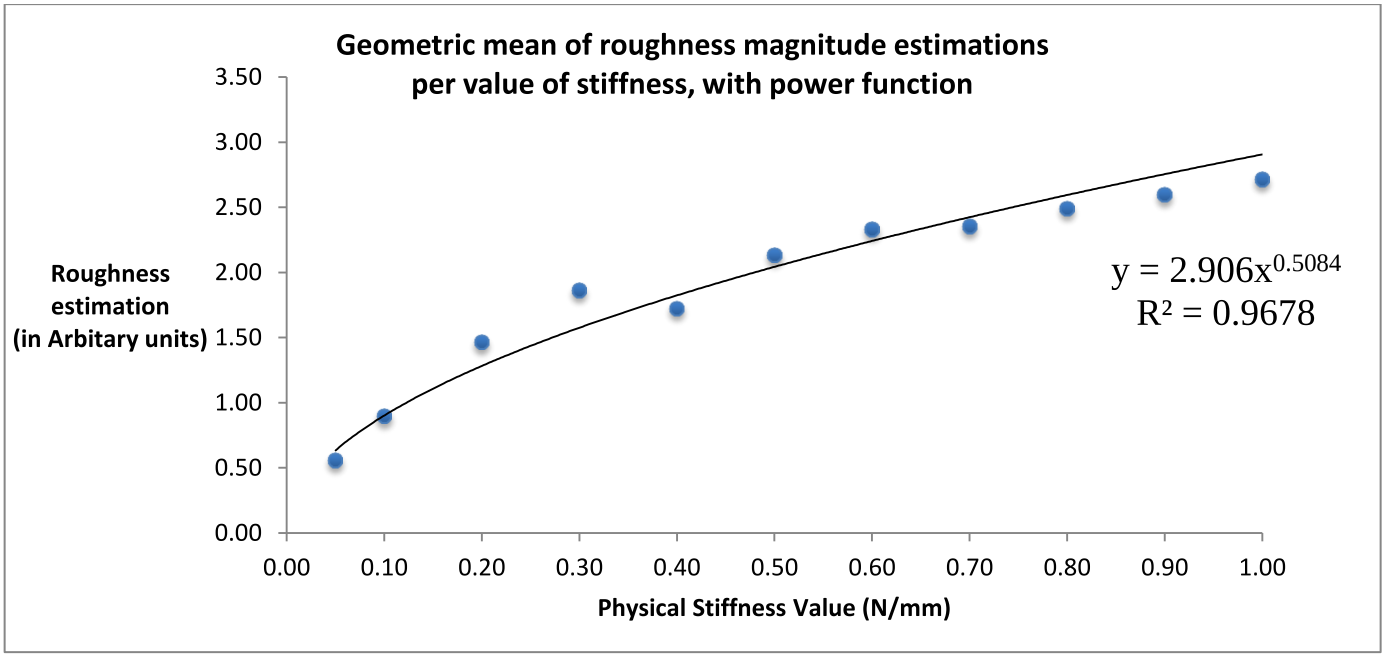

Fig. 4. Plot showing the relationship of physical stiffness and perceived roughness.

The geometric means were then plotted on a graph of roughness estimation ratios against the physical stiffness value for the comparison stimulus in N/mm (see Figure 4).

A power function was then calculated and plotted using these data. The high percentage of deviation that can be explained by this relationship ($R^2 = 0.968$) also shows that a power equation can be used to accurately describe the data gathered. The equation for this power function is:

$$\psi(I) = 2.906x^{0.5084} \quad (1)$$

This indicates that this relationship has a proportionality constant of 2.906 and an exponent of 0.5084, signifying that the perceptual magnitude grows more slowly than physical magnitude.

4. Discussion

It is clear from the graphs plotted using the data of this experiment that a strong relationship exists between the physical stiffness changes and the perception of roughness. More specifically, a power function is passed through the points obtained from the magnitude estimations with a high percentage of deviation that can be explained by this relationship ($R^2 = 0.968$).

A useful way of plotting data from magnitude estimations is through log-log coordinates. This kind of a plot allows an observer to determine if the data indeed follow a power function simply by observing if the points in the log-log coordinates follow a straight line. The plot below (see Figure 5) contains the same data seen in Figure 4 in log-log coordinates. A linear trend-line was passed through these points using a standard linear trend line function, which computes the equation for the linear best-fit line, by the method of least squares and standard deviation lines were also plotted, indicating the maximum and minimum error values. This plot again showed a high percentage of deviation that can be explained by this relationship (R^2 = 0.968) proving the points' linearity.

The data collected from this experiment also indicate that the sensation of roughness grows at a slower rate than the physical stimulus (stiffness) increase, with an exponent value indicated by *Stevens' Power Law* (Eq. 1.) to be 0.5084.

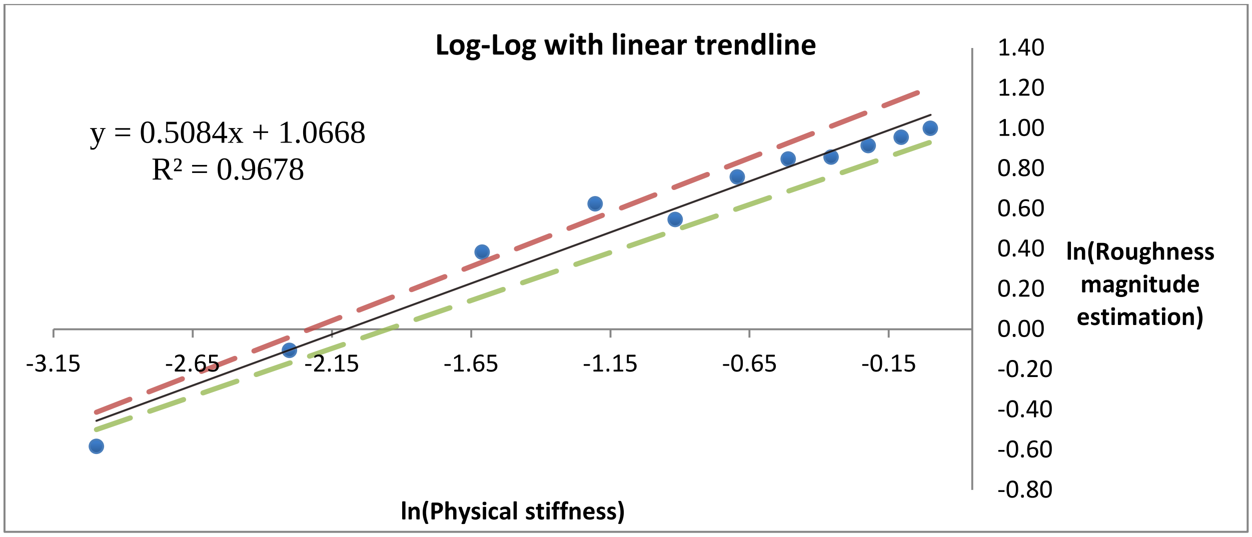

Fig. 5. Roughness magnitude estimation against physical stiffness values in log-log coordinates.

This exponent value is a lot smaller than the exponents measured by Stevens for a number of relevant continua. More specifically, Stevens (1975) found an exponent value for vibration continuum of 0.95 when a vibration stimulus of 60 Hz was applied to the finger and 0.60 when the frequency was increased to 250Hz. Also, when rubbing emery cloths, as the stimulus condition, an exponent of 1.50 was calculated and 0.80 for tactual hardness when squeezing rubber tested tactual roughness. If anything, one can say that the relationship of stiffness in the perception of roughness can most closely relate numerically to the relationship between the perception of brightness and the duration of the flashes (exponent of 0.50).

These values may potentially not mean anything when compared with the results obtained from this experiment simply because of the different conditions. In addition, Stevens was reported to use highly trained participants, which may have arguably affected his results. Also, all these exponents were measured with experiments in the "real world" environment with conditions extremely different that the ones used currently in this experiment (direct touch, emery cloths and vibrations).

At the moment of writing, there is no literature of how stiffness affects the perception of roughness in real, physical objects and what the value of the exponent of such relationship is to compare my data against.

5. Future Work

Aim of this section is to identify limitations in the work curried out and attempt to provide suggestions on how this piece of work can be extended further. The limitations identified exist mainly due to time, hardware and funding constraints during the progress of this study.

The Geomagic Touch force feedback device (FFD) used for the purpose of the experiment described above is fairly old and the actual device used has been used for a number of years by researchers for a number of different applications and experiments. It may worth investigating if the same results obtained with this device can be replicated, using a brand new device of the same make and model. Also it would be interesting repeating the same experiments with other FFDs of similar fidelity as the Geomagic Touch (such as the Novint Falcon[4]) or even with higher fidelity FFDs such as the Geomagic Phantom Premium 6DOF[5]. A higher fidelity FFD can render stiffness more accurately to the real world since it will be able to render stiffness values of much higher forces.

As a further work, it is worth investigating how other techniques for simulating physical attributes that produce the perception of roughness can be used to investigate the relationship between physical stiffness and roughness. In this study, the method of stick-slip was used for simulating roughness. As a future work, three-dimensional models of objects with a micro-texture rendered on them can be used, for example. Again their stiffness values would be altered, repeating the experiment to find the relationship of physical stiffness and the perception of roughness. These micro-textures can be either raised elements (similar to the surface of sandpaper) or a texture of ridges and lands as used by Lederman (1974) in her experiments of the perception of roughness.

6. Conclusion

Overall, the results showed a close relationship between physical stiffness and perceived roughness. More specifically, the average roughness magnitude estimation showed an increase with increasing physical stiffness in a rate that can be very closely described by a power function with a constant of proportionality equal to 2.906 and an exponent of 0.5084 (see Figure 4). Plotting the same data in log-log coordinate gave a straight line, further proving the existence of this relationship (see Figure 5).

Therefore, based on these results it can be concluded that physical stiffness plays a very important role in the perception of roughness, making harder objects feel rougher than softer[6] objects, even though their texture characteristics may remain constant.

Having in mind the existence of this relationship is a small step forward to a better understanding of touch as a sense that will help us move to the creation of better and more accurate haptic interfaces in the future, producing even more accurate representations of virtual haptic objects, as they exist in the real world.

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