FORCE FEEDBACK IN PSYCHOPHYSICS RESEARCH: EVEN LOW PERFORMANCE ALGORITHMS MAY LEAD TO REALISTIC PERCEPTUAL EXPERIENCE

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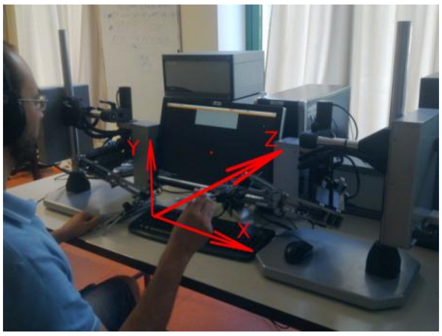
Abstract

Force feedback perception is relevant with many applications such as virtual simulation, 3D modeling or assembly/disassembly training. In this work we claim that the "1 KHz rule" (Coles, Meglan, & John, 2011) is not essential for the analysis of force feedback perceptual capabilities and we provide experimental evidences to support this statement. We implemented a virtual wall penetration task to study stiffness discrimination. Participants were asked to move a tool through a virtual wall (stiffness values: 331, 207, 83 N/m), and to immediately retract when it has been completely perforated. Three physics engine refresh rates have been tested (250, 500 and 1000 Hz) and performance of 8 participants have been analyzed in terms of overshoot error and velocity. No refresh rate effects emerged. We argue that force perception can be also investigated using low frequency rates: thus psychophysic studies are not bounded to expensive computers and devices.

Force perception studies date back to the first decades of XIX century, with the very first definition given in 1834 by Bell of *sense of force*, and the experiments of the German physiologist Ernst Weber (Jones, 1986).

Force perception is part of the more general haptic sense, which is currently defined as a perceptual system, mediated by the *cutaneous* and *kinesthetic* afferent systems (Lederman & Klatzky, 2009). Haptic perception includes: (a) tactile and thermic sensations, (b) kinesthetic perception, better known as proprioception, which concerns with the localization of own body parts position, and (c) force and weight perception of pressures applied to own body. This complex system uses perceptions derived from receptors embedded in the skin (*cutaneous* inputs) together with data provided by receptors embedded in muscles, tendons, and joints (*kinesthetic* inputs). The high number of differently situated receptors leads to a high variability in the features of receptors of the same kind, thus different type of haptic sensations have different sensitivity in frequency, intensity, and duration. For example, Brooks (1990) analyzes the requirements for telerobotic systems and sets them to 320 Hz for tactile sensation, 30 Hz for proprioception and 20 Hz for force sensation.

Robotic systems, when applied to surgery, may provide the surgeon with tools to increase their skills in complex tasks, mainly by reducing their errors. The main problem of robotic systems applied to surgery is the absence of touch sensation (Lanfranco, Castellanos, Desai, & Meyers, 2004). Furthermore, there is a lack of virtual reality training systems able to provide the surgeon with force feedback during the interaction with a realistic virtual environment (Okamura, 2009). Scientific research has made consistent efforts to fill this gap (i.e. Altomonte, Zerbato, Botturi, and Fiorini (2008), Zerbato, Baschirotto, Baschirotto, Botturi, and Fiorini (2011)), but a common limitation are the computational requirements of complex physical engines with high refresh rates. Physical engine refresh rates for force feedback are usually set in virtual simulators to 1 kHz (Coles et al.., 2011), in order to ensure a correct force-feedback perception, nevertheless Burdea (1996) sets the minimum refresh rate to 300 Hz, and Booth, Angelis, and Schmidt-Tjarksen (2003) find the minimum



acceptable haptic refresh rate ranged from 550 to 600 Hz.

Figure 2: The experimental setup involved an MPB Freedom 7S in the pen-hold grasping configuration.

In a previous study (Scandola, Vicentini, & Fiorini, 2011) two experimental force feedback tasks were performed in a virtual environment. The first experiment was based on a passive contact task, where an hand-grip was held by the subject waiting for the force feedback perception given by the contact with virtual objects. The second one was an active contact task, in which a tool was moved in a direction until the contact perception with a pliable object. Different stiffnesses and refresh rates were factorially manipulated. The overall result of these experiments showed an improved sensitivity in almost all variables considered with refresh rates of 500 and 1000 Hz compared with a refresh rate of 250 Hz, but no improved sensitivity was shown among them.

In this work we evaluate the user's perceptual capabilities in a haptic-based experiment by manipulating stiffness and refresh rates conditions. The task requires the subjects to move the tool against an invisible virtual wall, to pass through it, and to immediately retract after the complete penetration. Perceptual abilities involved in a *passing through a pliable object* task are more complex than those required in "simple" *contact task*: the participant has to perceive not just the starting point of the haptic stimulus, but its ending point. In case no differences were observed among high and low refresh rates conditions, we could conclude that high-frequency systems aren't necessarily required to simulate a realistic haptic environment. Therefore it could be argued that haptic perception can be investigated even with low frequency rates. This would mean that psychophysic studies are significant even when conducted without expensive computers and computer science experts, allowing for more and more studies by psychophysics experts.

Methods

We tested subjects' perceptual capabilities in stiffness discrimination with different physical engine refresh rates. The active task required the participant to move the tool against and through a virtual wall and to immediately retract at the end of the perceived haptic feedback. Several different experimental conditions were evaluated by providing refresh rates values of 250 (that is the optimal perception for Pacinian corpuscoles), 500 or 1000 Hz and stiffness values of 83 (the stiffness of the human fat), 331 (the stiffness of the human skin), or 207 N/m (the average between 331 and 83). Refresh rates and stiffness conditions were randomized for each participant, and every combination was repeated 15 times, for a total of 135 trials. Each experiment took about 20 minutes. Penetration depth beyond the virtual wall and penetration velocity were logged for statistical analysis.

Apparatus

To simulate realistic force feedbacks we used a Freedom 7S force-feedback haptic device (MPB Technologies, Montreal, Quebec), which provides a workspace of about 170 W x 220 H x 330 D mm. The Freedom is a high performance device, with a position resolution of 2 μm, a resolution in force rendering of 40 mN and a maximum update rate above 1 kHz. The base of this device was positioned so as to be comfortably reached with the subject's dominant hand. The pen-hold grasping configuration involved the thumb, index, and middle fingers. The hand operating the device is not anchored to the desk, hence neither the wrist nor the elbow were provided with a grounded support. For the visual rendering we used a 22-inch wide screen monitor, placed in front of the subject (see Figure 1). The visual scene for our experiment was generated using the OpenGL library and rendered on the monitor.

Participants

8 subject (1 female) contributed to the collection of experimental data. They were aged from 20 to 36, all experienced with haptic devices and right-handed. All of them were recruited within the laboratory staff and were not inform about the experiment goals but simply instructed about how to attend to the task. All the participants have a normal sense of touch and used their dominant hand to perform the task.

Procedure

We instructed participants saying that: "You have to move the tool close-far along an imaginary line (see Figure 1) until touching and passing through the virtual wall you will perceive. When you perceive that you are beyond the virtual wall we ask you to get immediately back toward the starting position".

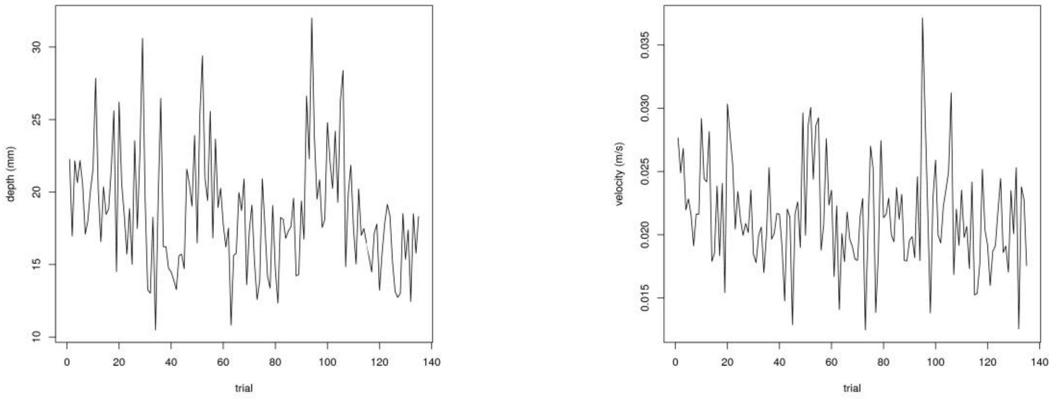
In the visual scene we represented a small red sphere which acted as a proxy for the position of the tool tip in the virtual world. The virtual wall was not visually rendered, in order to avoid that the location of the surface contact point affected the participants response. The virtual wall depth varied randomly between 2 and 4 mm.

Statistical Analysis

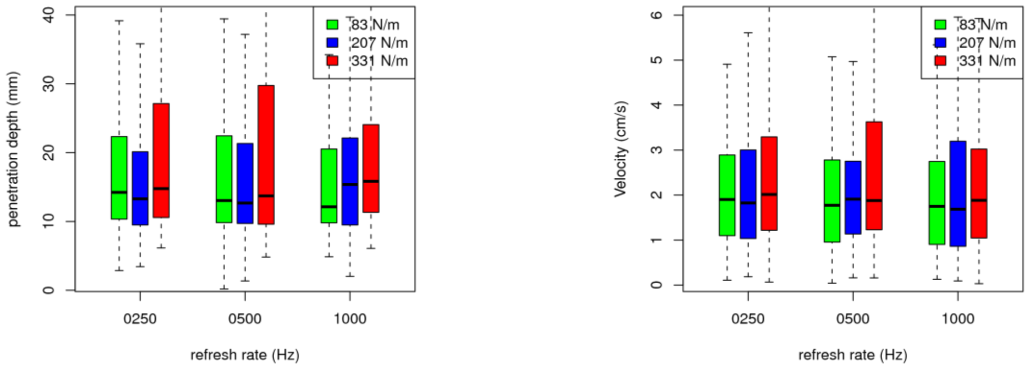
Statistical analysis were conducted separately for each subject and for aggregate data. Repeated measures analysis of variance (RM-ANOVA) were used to verify the statistically significance of the obtained differences due to the variance of stiffness and refresh rates values. In addition, the Tukey's Honestly Significant Difference (HSD) post-hoc test was used to identify clusters significantly different in their mean values (Levin & Fox, 2000).

Results

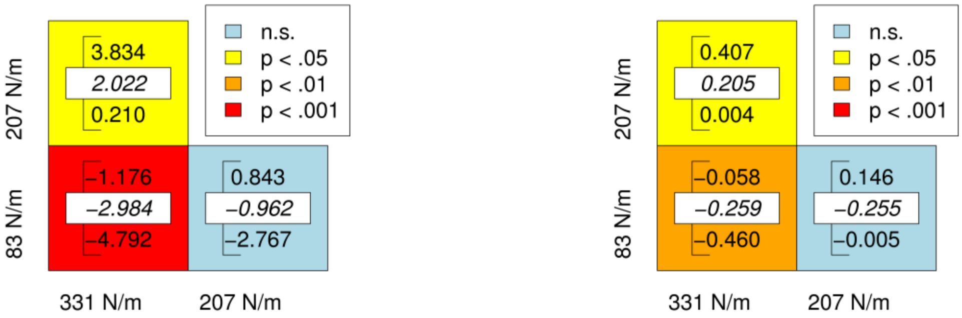
To identify possible learning effect that may invalidate the analysis we checked the statistically significance of the dependent variable's variance among trials. As depicted from Figures 2(a) and 2(b) our analysis showed the lack of difference among trials in penetration depth (F, p=0.99)and penetration velocity (F, p=0.99). These results justify the assertion that there was no significant learning effect.



(a) Penetration depth (b) Penetration velocity



(c) Penetration depth (d) Penetration velocity



(e) Penetration depth (f) Penetration velocity

Figure 2: In the upper part we show the learning curves (Figures 2(a), 2(b)): penetration depth and penetration velocity are plotted against trials. In the middle boxplots (Figures 2(c), 2(d), the aggregate data show median values and interquartile ranges). In the lower part we present plots for HSD tests (Figures 2(e), 2(f), color boxes represent the statistical significance, values in the white box represent the difference between cluster means, and values over and under the box represent 95% confidence intervals.

	250 Hz	**500 Hz**	**1,000 Hz**	**Total**
83 N/m	18.78 (18.88)	16.69 (9.93)	16.35 (11.47)	*17.28* *(12.69)*
207 N/m	17.63 (12.67)	16.58 (9.55)	20.45 (18.15)	*18.24* *(14.02)*
331 N/m	20.25 (13.89)	20.75 (14.81)	19.76 (13.17)	*20.26* *(13.95)*
Total	*18.88* *(14.21)*	*18.02* *(11.83)*	*18.85* *(14.64)*	**18.59** **(13.61)**

(a) Penetration depth

	250 Hz	**500 Hz**	**1,000 Hz**	**Total**
83 N/m	2.11 (1.38)	1.98 (1.33)	2.05 (1.49)	*2.05* *(1.40)*
207 N/m	2.11 (1.38)	2.07 (1.27)	2.12 (1.65)	*2.10* *(1.44)*
331 N/m	2.32 (1.52)	2.43 (1.66)	2.16 (1.51)	*2.31* *(1.57)*
Total	*2.18* *(1.43)*	*2.16* *(1.44)*	*2.11* *(1.55)*	**2.15** **(1.47)**

(b) Penetration velocity

Table 1: Penetration depth (mm) and Penetration velocity (cm/s) for refresh rate and stiffness conditions. Data reported as Mean (SD)

Penetration depth beyond the wall

Penetration depth analysis shows neither statistical significance for refresh factor nor for interaction, while the main effect stiffness raised the statistical significance (F = 4.49, $p=0.011$). Data are summarized in Figure 2(c) and Table 1. The HSD post-hoc test for factor stiffness (summarized in Figure 2(e)) shows that cluster means are different between 331 and 207 ($p<0.05$) and between 331 and 83 ($p<0.001$) groups, whereas there is no difference between 207 and 83 N/m groups.

Penetration velocity of the wall

Penetration depth analysis shows no statistical significance for stiffness factor nor interaction, whereas the main effect refresh rates raises the statistical significance (F = 14.14, $p<0.001$). Data are summarized in Figure 2(c) and Table 1. The HSD test for stiffness (summarized in Figure 2(f)) shows similar results to penetration depth data. There are differences between 331 and 207 ($p<0.05$) and between 331 and 83 ($p<0.01$) groups but there is no difference between 207 and 83 N/m groups.

General Discussion And Conclusion

The present study shows no refresh rate effect but only an improved sensitivity in haptic perception in 331 and 207 N/m stiffness values respect to 83 N/m. These findings are in agreement with previous works, in which different stiffness values lead to different haptic sensitivity (Vicentini & Botturi, 2010a, 2010b). These results are in partial agreement with Scandola et al.. (2011), where it was showed that high refresh rates are not mandatory for an optimal force-feedback perception. In Booth et al.. (2003), Scandola et al.. (2011), no stiffness factor effect was found. In both studies the Authors highlighted the impossibility to generalize their findings to other experimental conditions, because stiffness effects can be hidden by refresh rates effects, or may be caused by specific characteristics of the experimental design.

The findings of this study, involving a more complex perceptive (and maybe more ecological) task compared with the just mentioned ones, show the relevance of the stiffness factor. Therefore, considering the wide scientific literature according with the presence of the stiffness factor in force-feedback perception, we conclude that stiffness factor may be considered a factor of utmost importance in force-feedback perception.

The lack of effects of refresh rates factor, together with previous findings (Scandola et al.., 2011), show that the use of high performance computers or very complex real-time algorithms for force-feedback simulation is not mandatory, allowing the study of force perception with general psychophysical methods also without dedicated computer science experts: even simple algorithms lead to optimal perceptual performance in pliable environments.

Acknowledgments

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