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How force perception changes in different refresh rate conditions

Michele Scandola, Marco Vicentini and Paolo Fiorini

Abstract— **In this work we consider the role of different refresh rates of the force feedback physical engine for haptics environments, such as robotic surgery and virtual reality surgical training systems. Two experimental force feedback tasks are evaluated in a virtual environment. Experiment I is a passive contact task, where the hand-grip is held waiting for the force feedback perception given by the contact with virtual objects. Experiment II is an active contact task, where a tool is moved in a direction until the contact perception with a pliable object. Different stiffnesses and refresh rates are factorially manipulated. To evaluate differences in the two tasks, we account for latency time inside the wall, penetration depth, and maximum force exerted against the object surface. The overall result of these experiments shows an improved sensitivity in almost all variables considered with refresh rates of 500 and 1,000 Hz compared with a refresh rate of 250 Hz, but no improved sensitivity is showed among them.**

I. Introduction

Robotic systems applied to surgery offer surgeons enhanced skills for complex tasks at first by reducing errors. This reduction in errors likely derives from the improved visualization and dexterity afforded by the robotic system. And ultimately, fewer errors means greater safety for patients [1]. Robotic surgery was first developed in urology using robot-assisted laparoscopy successfully for performing radical prostatectomies, and the use of robotic assistance in surgical operations grew with more than 55,000 radical prostatectomies performed with da Vinci (© Intuitive Surgical, Inc., Sunnyvale, CA) robotic assistance in the United States in 2007 and more than 70,000 performed worldwide in 2008 [2]. Robot-assisted laparoscopic surgery was quickly spread in Europe and other parts of the world, and in the fields of cardiothoracic, gynecologic, and general surgery.

Virtual reality (VR) surgical training systems allow interaction using a laparoscopic-like interface, such as a laparoscopic frame with modified laparascopic instruments [3]. Several VR laparoscopic training systems are available on the market. The most cited in the literature are the Minimally Invasive Surgical Trainer-Virtual Reality (MIST-VR; Mentice AB, Gothenburg, Sweden), the LapSim virtual reality laparoscopic simulator (Surgical Science, Gothenburg, Sweden) [4], Xitact LS500 laparoscopic cholecystectomy simulator (Xitact SA, Morges, Switzerland) [5], and LapMentor (Simbionix USA Corp., Cleveland, OH) [6], [7].

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Authors' address: Altair Lab, Computer Science Department, University of Verona, Ca' Vignal 2, Strada Le Grazie, 15, I-37134 Verona, Italy. E-mail: {michele.scandola, marco.vicentini, paolo.fiorini} @metropolis.sci.univr.it.

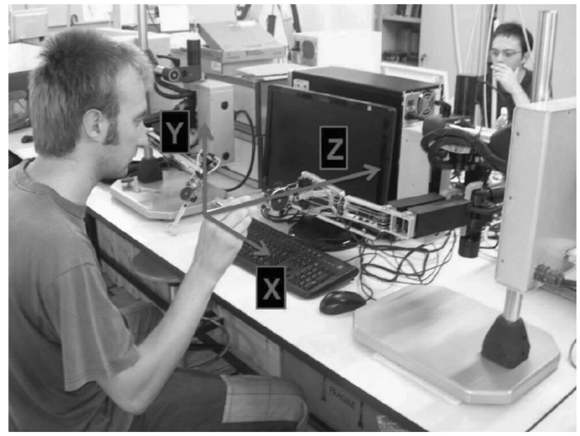

Fig. 1. The experimental setup for Experiment II involved an MPB Freedom 7S in the pen-hold grasping configuration. Reference direction is the z axis (hand movement is close-far).

The advantage of contemporary robot-assisted laparoscopy is clear: the open-surgery practitioner can use the three-dimensional imaging and additional degrees of freedom provided by the robot to complete individual complex tasks efficiently. The main problem of robotic systems applied to surgery is the absence of touch sensation [8], [9]. There is a lack of VR training systems where surgeons can experience the force feedback from a "real" virtual environment [10].

Although VR holds great promise to expand the scope of laparoscopic simulation, current interfaces may limit their utility for surgical training. For enhancing the validity of those VR simulators, in scientific research there are several studies to introduce haptic feedback in these systems [11], [12], [13], [14], [15], [16], [17], but often computational resources are limited by complex physical engines with high refresh rates.

Physical engine refresh rates for force feedback are usually set in virtual simulators to 1,000 Hz [18], in order to ensure a correct force-feedback perception, but Burdea [19] sets the minimum refresh rate to 300 Hz, and in the telerobotic field [20] sets response requirements to 320 Hz for tactile sensation, 30 Hz for proprioception and 20 Hz for force sensation. In a study by Booth [21] the minimum acceptable haptic refresh rate found was ranged from 550 to 600 Hz, irrespective of material stiffness. This is an untypical result, because several authors [22], [23] said that there is an improvement of haptic perception in higher stiffness conditions. There is still little information concerning the correct refresh rate for the physical engine and the effects on the user's performance. In [18] an interaction effect between refresh rates and stiffness is explained: softer virtual objects are adequately perceived in lower refresh rates, while harder virtual objects in higher refresh rates show an improved human perception sensitivity. Understanding how force perception in virtual simulators is affected by force feedback refresh rates is of utmost importance in robotic surgery and virtual surgical simulators, because an imperfect force feedback means an imperfect force perception, which in virtual surgical simulators means a "not so good" learning, but in robotic surgery can affect patient safety. Besides, an high refresh rate requires high-bandwidth and a large amount of critical processing resources which could involved in further tasks.

In this work we evaluate the user's perceptual capabilities in two haptic-based experiments with different refresh rates. The first experimental condition is a passive task where a virtual object "moves against" the participant; the second one is an active task where the goal is to move the tool until it takes contact with a virtual wall. In both conditions our goal is to identify how the refresh rates of the physical engine is relevant to the force feedback perception.

II. METHODS

We tested the perceptual capabilities in stiffness discrimination with different physical engine refresh rates. The first experiment was a passive task in which the wall is moving against the tool and the hand hold the haptic device handgrip passively waiting for the impact. The second experiment considered an isometric condition aimed at reaching a virtual wall by moving a tool. Each experiment was evaluated according to different experimental conditions, by involving different refresh rates at 250 (that is the optimal perception for Pacinian corpuscoles), 500 and 1,000 Hz and different stiffness of the pliable surface (40, 120 and 250 N/m).

A. Apparatus

To simulate realistic force feedbacks we involve a Freedom 7S force-feedback haptic device (MPB Technologies, Montreal, Quebec), which allows for 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, a maximum update rate greater than 1 kHz. The base of this device is positioned so as to be comfortably reached with the subject's dominant hand. The pen-hold grasping configuration is involved by concurrently using the thumb, index, and middle fingers. The hand operating the device is not anchored to the desk, hence neither the wrist nor the elbow is provided with a grounded support. For the visual rendering we use a 22-inch wide screen monitor, placed in front of the subject (see Figure 1). The visual scene for our experiment is generated using the OpenGL library and displayed on the monitor. The force feedback returned by the haptic device is generated by a custom C++ program, founded on the provided Freedom API. The running O.S. is Ubuntu 9.04. Penetration depth, latency time inside the virtual wall, and maximum force exerted against the virtual wall are logged for statistical analysis. Force F_p is rendered according to the linear model $F_p = -k \cdot D_p$ where k is the stiffness value, D_p is the penetration inside the virtual surface.

B. Participants

A total of 7 participants have been examined for Experiment I, and 8 (6 of them have participated to the previous one) for Experiment II (age range from 23 to 36 in both experiments, all male, right-handed, and experienced with haptic devices). All the participants were recruited within the laboratory staff. They were not informed about the experiment goals and were simply instructed how to attend to the task. All the participants have a normal sense of touch and used their dominant hand to perform the task.

C. Statistical Analysis

Statistical analysis were conducted separately for each subject and for aggregate data. Repeated measures analysis of variance (RM-ANOVA) were used to determine whether there were statistically significant differences due to stiffness or refresh rate factors. Statistical analysis results report the main effects (also called first-level effects), that is, a factor considered alone, and the interaction effects (also called second level effects) that is, the effect of the interaction between two factors.

In addition, the Tukey's Honestly Significant Difference (HSD) [24] post-hoc test was used to identify which cluster means were significantly different from others. In aggregate data analysis a factor for individual subject was included to avoid that differences between subjects were counted as random variation, in order to enhance the sensitivity to the stimulus parameter variation.

III. EXPERIMENT I

This experiment was aimed at identifying how human capabilities in stiffness discrimination change according to different refresh rates of physical engine in a passive task. As detailed in [25], we measured the maximum penetration depth, the exerted force, and the latency time inside the virtual wall.

A. Procedure

The participants were instructed with this sentence: "You have to firmly hold the tool waiting the contact with a pliable surface moving toward you and, immediately upon feeling the haptic sensation, press a button on the keyboard". In order to have the maximum concentration from participants, an "haptic shake" was applied to the tool and a rendered red small sphere changed its color from red to yellow to announce the beginning of the trial. After a random amount of time (mean 750 ms) the virtual wall began its movement at 17 mm/s, letting the force feedback of the virtual wall hitting the tool to be applied. The virtual wall was not visually rendered, in order to avoid to bias participants with respect to the location of the surface contact point. 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.

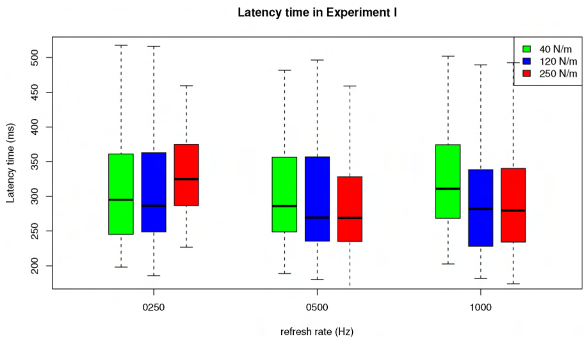

Fig. 2. Latency time inside (ms) the wall in Experiment I. Aggregate data show median values and interquartile ranges (lower bound, first and third quartile, upper bound).

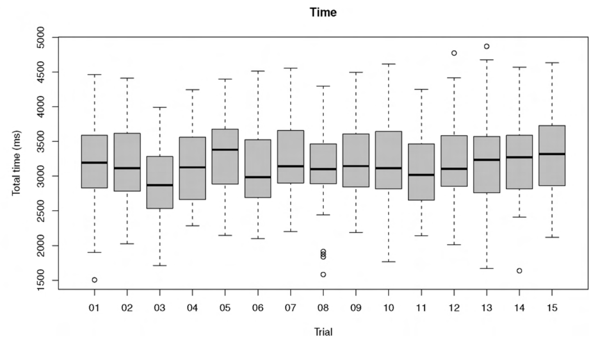

Fig. 3. Learning curve of Experiment I: total time (ms) vs trial number. Aggregate data show median values and interquartile ranges (lower bound, first and third quartile, upper bound).

TABLE I
LATENCY TIME (MS) IN EXPERIMENT I FOR REFRESH RATE AND STIFFNESS. DATA REPORTED AS MEAN (SD)

	250 Hz	**500 Hz**	**1,000 Hz**	**Total**
40 N/m	321.84 (122.31)	302.03 (69.22)	327.62 (82.10)	*317.16 (94.30)*
120 N/m	309.92 (87.21)	295.90 (74.49)	303.26 (94.82)	*303.00 (85.73)*
250 N/m	338.56 77.66	283.31 63.50	296.38 80.42	*306.09 77.69*
Total	*323.40 (97.90)*	*293.77 (69.48)*	*309.08 (96.78)*	**308.75 (86.28)**

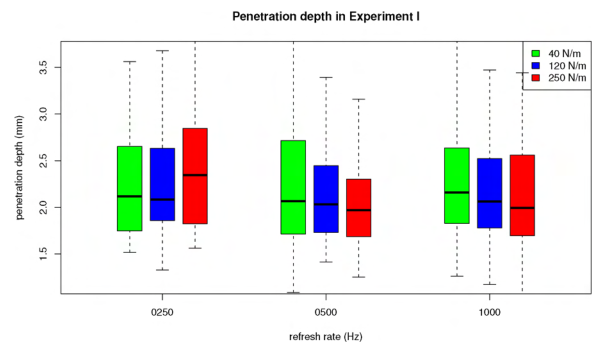

Fig. 4. Virtual wall penetration (m) in Experiment I. Aggregate data show median values and interquartile ranges (lower bound, first and third quartile, upper bound).

B. Results

Learning effects among trials were checked for total time completion task. Figure 3 shows the learning curve, statistical analysis showed that there was no statistically significant differences among trials in total time ($F_{14;900}$ = 1.54, p = 0.09). These results justified the assertion that there was not any significant learning effect even in Experiment I. Repeated-Measure Analysis of Variance (RM-ANOVA) were conducted on latency time inside the wall, maximum force exerted against the virtual wall and virtual wall penetration.

1) Latency time: Figure 2 and table I showed latency time results. Each first-level effect reaches the statistical significance, that are stiffness ($F_{2;852}$ = 3.79, p = 0.02) and refresh rate ($F_{2;852}$ = 15.13, $p < 0.001$). Interaction was also significant ($F_{4;852}$ = 4.56, $p = 0.001$). The HSD test showed that in latency times grouped by stiffness there was difference only between 40 and 120 N/m groups, while in latency times grouped by refresh rates there were significant differences in every group.

2) Penetration depth: Penetration depth analysis showed no statistical significance for stiffness factor nor interaction, while the main effect refresh rates raised the statistical significance ($F_{2;852}$ = 14.14, $p < 0.001$). Data are summarized in Figure 4 and Table II. HSD post-hoc test of refresh rates showed that cluster means were different between 500 and 250 and between 1,000 and 250 groups, while there was no difference between 1,000 and 500 Hz groups.

3) Maximum force exerted against the virtual wall: Maximum force data are summarized in Figure 5 and Table III. Maximum forces data analysis showed that the refresh rate factor ($F_{2;852}$ = 22.36, $p < 0.001$) was statistically significant. As for penetration depth, the HSD test in maximum forces grouped by refresh rates showed that there were differences between 250 and 500 Hz, between 250 and 1,000 Hz, but there was no difference between 500 and 1,000 Hz.

C. Discussion

The factor Refresh rates shows an improved sensitivity in force feedback perception in 500 and 1,000 Hz conditions, compared to 250 Hz condition, in penetration depth and maximum force exerted. In latency time this factor shows a better sensitivity in the 500 Hz condition than in 1,000 Hz condition, which is better than 250 Hz condition. As expected [25], the stiffness factor reaches the statistical significance just in latency time measurements, showing an improved sensitivity in the 40 N/m condition respect to 120 N/m condition, but there is no difference among 250 N/m and 40 N/m conditions, nor 250 N/m and 120 N/m conditions.

The interaction between stiffness and refresh rates factors reaches the statistical significativity in latency time mainly thanks to two groups (40 N/m - 1,000 Hz and 250 N/m - 250 Hz).

TABLE II

PENETRATION DEPTH (MM) IN EXPERIMENT I FOR REFRESH RATE AND STIFFNESS. DATA REPORTED AS MEAN (SD)

	250 Hz	**500 Hz**	**1,000 Hz**	**Total**
40 N/m	2.28 (0.67)	2.22 (0.62)	2.28 (0.62)	*2.26 (0.63)*
120 N/m	2.27 (0.61)	2.16 (0.54)	2.21 (0.63)	*2.21 (0.59)*
250 N/m	2.38 (0.60)	2.10 (0.54)	2.18 (0.63)	*2.22 (0.60)*
Total	*2.31 (0.63)*	*2.16 (0.57)*	*2.22 (0.62)*	**2.23 (0.61)**

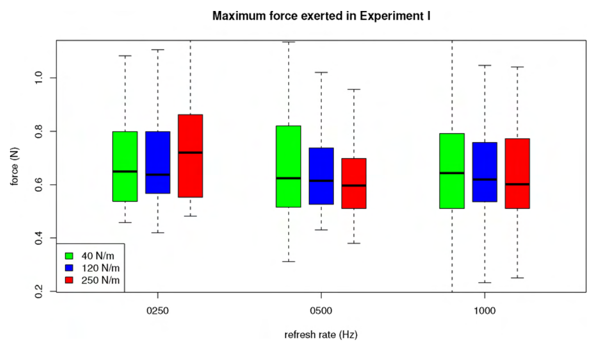

Fig. 5. Maximum force exerted (N) against the virtual wall in Experiment I. Aggregate data show median values and interquartile ranges (lower bound, first and third quartile, upper bound).

IV. EXPERIMENT II

The aim of this experiment was to understand how different refresh rates could modify active stiffness perception. We assessed the same variables of the Experiment I.

A. Procedure

We instructed participants saying that: “You have to move the tool close-far along an imaginary line (see Figure 1) until touch the virtual wall and to immediately get back to 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.

TABLE III

MAXIMUM FORCE EXERTED (N) IN EXPERIMENT I FOR REFRESH RATE AND STIFFNESS. DATA REPORTED AS MEAN (SD)

	250 Hz	**500 Hz**	**1,000 Hz**	**Total**
40 N/m	0.69 (0.20)	0.67 (0.19)	0.63 (0.26)	*0.66 (0.22)*
120 N/m	0.69 (0.18)	0.65 (0.17)	0.67 (0.19)	*0.67 0.18*
250 N/m	0.73 (0.18)	0.63 (0.16)	0.64 (0.20)	*0.67 0.19*
Total	*0.70 (0.19)*	*0.65 (0.17)*	*0.65 (0.22)*	**0.67 (0.20)**

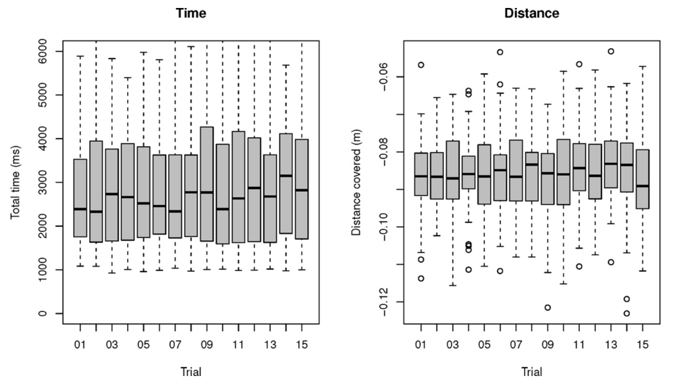

Fig. 6. On the left time learning curve of Experiment II: trial number vs total time (ms). On the right total distance covered learning curve of Experiment II: trial number vs covered distance (m). Aggregate data show median values and interquartile ranges (lower bound, first and third quartile, upper bound).

Stiffness, refresh rates levels and number of trials were the same of Experiment I randomized between participants.

B. Results

In order to avoid the suspicion of a learning effect which could affect the analysis, we checked whether among trials total time and distance covered change in a statistically significant way. As depicted from Figure 6 our analysis showed that there was no difference among trials in total time ($F_{14;1044} = 0.56$, $p = 0.90$) and distance covered ($F_{14;1044} = 0.70$, $p = 0.78$). These results justified the assertion that there was no significant learning effect.

Repeated-Measure Analysis of Variance (RM-ANOVA) were conducted on latency time inside the wall, maximum force exerted against the virtual wall and virtual wall penetration.

1) Latency time: Latency time results are showed in Figure 7 and Table IV. Latency time data analysis showed that the refresh rate factor ($F_{2;987} = 12.69$, $p < 0.001$), the stiffness factor ($F_{2;987} = 26.52$, $p < 0.001$), and the interaction between stiffness and refresh rate ($F_{4;987} = 21.74$, $p < 0.001$) were statistically significant. The HSD test showed that latency times grouped by stiffness were always different, while in latency times grouped by refresh rates there were differences between 250 and 500 Hz, between 250 and 1,000 Hz, but there was no difference between 500 and 1,000 Hz.

2) Maximum force exerted against the virtual wall: The maximum force applied to the tool in contact with the virtual wall were logged and Figure 8 and Table V show them. Maximum forces data analysis showed that the refresh rate factor ($F_{2;987} = 10.08$, $p < 0.001$) and the interaction between stiffness and refresh rate ($F_{4;987} = 9.40$, $p < 0.001$) were statistically significant. As for latency time, the HSD tests in maximum forces grouped by refresh rates showed that there were differences between 250 and 500 Hz, 250

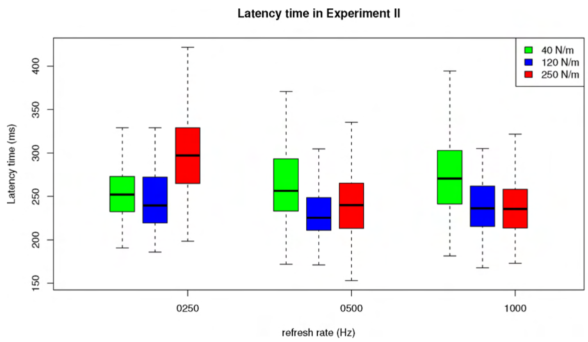

Fig. 7. Latency time (ms) inside the wall in Experiment II. Aggregate data show median values and interquartile ranges (lower bound, first and third quartile, upper bound)

TABLE IV

LATENCY TIME (MS) IN EXPERIMENT II FOR REFRESH RATE AND STIFFNESS CONDITIONS. DATA REPORTED AS MEAN (SD)

	250 Hz	500 Hz	1,000 Hz	Total
40 N/m	261.97 (61.26)	275.58 (82.18)	294.24 (101.45)	*277.26 (84.08)*
120 N/m	253.13 (65.48)	234.17 (37.51)	243.31 (37.69)	*243.62 (49.32)*
250 N/m	310.41 (76.79)	246.41 (51.69)	240.44 (39.82)	*265.84 (66.18)*
Total	*275.10 (72.48)*	*252.14 (62.47)*	*259.48 (71.04)*	**262.27 (69.41)**

and 1,000 Hz, but there was no difference between 500 and 1,000 Hz.

3) Penetration depth: Data collected for penetration depth is showed in Figure 9 and in Table VI. Data analysis showed no statistical significant mean effects, but the interaction between stiffness and refresh rate ($F_{4;987} = 3.55$, $p = 0.007$) was statistically significant.

C. Discussion

The data here collected show a similar trend to the ones of Experiment I. Penetration depth does not seem to improve its sensitivity in relation to different conditions of stiffness and refresh rates, while maximum force exerted and latency time seem to suggest an improved sensitivity in refresh rates conditions bigger than 250 Hz.

TABLE V

MAXIMUM FORCE (N) EXERTED IN EXPERIMENT II FOR REFRESH RATE AND STIFFNESS CONDITIONS. DATA REPORTED AS MEAN (SD)

	250 Hz	500 Hz	1,000 Hz	Total
40 N/m	1.41 (1.39)	1.58 (2.02)	1.01 (1.40)	*1.34 (1.64)*
120 N/m	1.41 (1.72)	0.82 (0.96)	1.38 (1.31)	*1.21 (1.39)*
250 N/m	1.56 (1.69)	1.19 (1.12)	0.95 (1.46)	*1.24 (1.46)*
Total	*1.46 (1.60)*	*1.20 (1.48)*	*1.11 (1.40)*	**1.26 (1.50)**

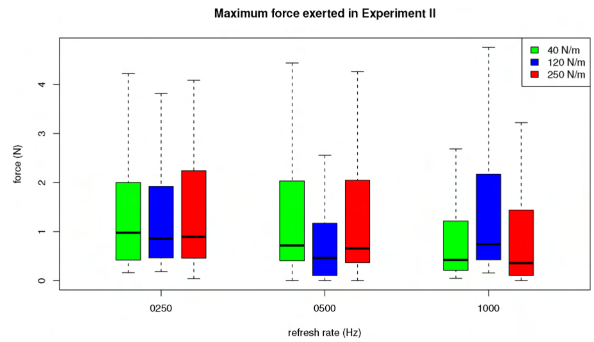

Fig. 8. Maximum force (N) exerted against the virtual wall in Experiment II. Aggregate data show median values and interquartile ranges (lower bound, first and third quartile, upper bound).

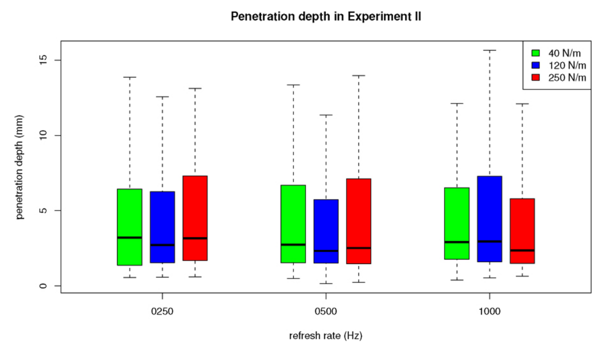

Fig. 9. Virtual wall penetration (m) in Experiment II. Aggregate data show median values and interquartile ranges (lower bound, first and third quartile, upper bound).

The interaction between stiffness and refresh rates in all three indexes considered shows us how different refresh rates seem to have a sort of "diagonal effect", to put it better we have a greater sensitivity in penetration depth and latency time for the softer stiffness (40 N/m) with the lower refresh rate (250 Hz), for the medium stiffness (120 N/m) with the medium frequency (500 Hz), and for the harder stiffness (250 N/m) with the higher frequency (1,000 Hz), a similar effected is reported in [18]. This effect in maximum force exerted is also present with 120 N/m - 500 Hz and 250 N/m - 1,000 Hz combinations, but not in 40 N/m - 250 Hz combination.

V. GENERAL DISCUSSION AND CONCLUSION

In these experiments, the stiffness factor shows unclear effects on force perception, reporting results different from previous findings [25], [26]. In both tasks the stiffness factor is not significant except for latency time, as also reported in [21]. In this last study the Authors highlighted that it is important not to generalize their findings to other experimental conditions. Even if we also recommend not to generalize our results, we argue that it may be acceptable to hypothesize for lack of effect of the stiffness factor over a refresh rate factor. These can be due for the passive nature of

TABLE VI

PENETRATION DEPTH (MM) IN EXPERIMENT II FOR REFRESH RATE AND STIFFNESS CONDITIONS. DATA REPORTED AS MEAN (SD)

	250 Hz	500 Hz	1,000 Hz	Total
40 N/m	4.64 (4.55)	5.53 (6.62)	4.93 (4.68)	*5.03 (5.36)*
120 N/m	4.67 (5.72)	3.98 (3.67)	4.81 (4.41)	*4.49 (4.69)*
250 N/m	5.36 (5.61)	4.31 (3.68)	4.29 (4.72)	*4.65 (4.75)*
Total	*4.89 (5.32)*	*4.61 (4.90)*	*4.68 (4.60)*	**4.72 (4.94)**

the first task, and for the lack of control on tool movement (participants could freely move the tool at the speed they wanted) for the second one. Maybe these features could have affected stiffness perception.

Globally our findings show an improved sensitivity in haptic perception in 500 and 1,000 Hz refresh rate conditions respect to the 250 Hz one. These results are consistent with [20] indications for tactile perception (320 Hz).

Further investigations are still necessary with a larger sample size and different experimental conditions, i.e. investigating how the force feedback refresh rate affects force, stiffness, and size discrimination, and how it is modulated along the remaining axis and directions (close-far and far-close, left-right and right-left, top-down and bottom-up)

Application-oriented work will focus on implementing methods that take into account our perceptual findings; more specifically, our chosen context is a tele-operated surgical scenario, in which accuracy is a critical goal. Further work is necessary to better understand which is the best frequency for force feedback in relation with human capabilities and technical instruments characteristics, in order to ensure correct learning processes in virtual simulators and a better patient safety in robotic surgery.

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