MEASURING PLIABLE PERCEPTION CAPABILITIES IN TELEOPERATED AND VIRTUAL ENVIRONMENTS

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Abstract

Surgical simulation offers surgeons an opportunity to enhance surgical safety, by practicing advanced skills outside the operating room before attempting them on living patients. In this work we compare perceptual capabilities in teleoperated environment, in virtual one, and in direct hand-object manipulation, by benchmarking two tasks which constitute the palpation procedure. In the first task we account for perceptual capabilities in stiffness discrimination, while in the second one the capabilities in size discrimination. Data collected in teleoperated setup did not differ from the one collected in real hand-object manipulation, nor in virtual environment. Subjects assessed the physical peculiarities of the object, identified the spatial position, and distinguished different roughness. These results should be considered as a proof of the constancy of the perceptual capabilities in haptics within different environments.

Contemporary robotic systems offer surgeons enhanced skills for complex tasks at first by reducing errors. This reduction in errors likely derives from the improved visualization and dexterity provided by the robotic system. And ultimately, this means greater safety for patients (Chang, Satava, Pellegrini, & Sinanan, 2003). But, like any new technology, surgical robotics requires dedicated training to achieve mastery. Current available literature demonstrates that surgical performance and dexterity can be proficiently achieved and objectively measured using a virtual reality system and that this may have important implications in training future surgeons.

Virtual reality training systems are not currently realistic reconstruction of the live operating environment because they lack tactile sensation. In addition they do not represent a complete intervention, nor account for the specific patient's anatomy. A complete solution where the surgeons can experience the force feedback from a "real" virtual environment with haptic devices is not present yet on the market (Okamura, 2009). Therefore a solution that can give the possibility to provide a force feedback, and assess the realism of the experience should be investigated to improve the performance of present training system. There is little information concerning the essential skills that must be trained and assessed for a complete operation as well for specific sub-tasks.

In this work, we evaluate the user's perceptual capabilities in two haptic based test-beds which constitute the core of a palpation task, the fundamental part of a physical examination in which an organ is felt to determine its size, shape, firmness, or location, by active touching its surface (Vicentini & Botturi, 2010b). Such test-beds will allow to train novice surgeons in situations from the virtual to real world of an operating room, and to evaluate their proficiency level, prior to participating in live cases.

Figure 1: (a) the teleoperation setup involving the NASA-JPL Force Reflecting Hand Controller and the Staubli Puma 200. (b) the setup for the direct hand-object manipulation. (c) the virtual environment setup involved a MPB Freedom 7S in the pen-hold grasping configuration.

Methods

In the first task we test the perceptual capabilities in stiffness discrimination, while in the second one the capabilities in size discrimination. Each task will be evaluated according to different experimental conditions, by involving a teleoperation environment, a direct hand-object manipulation, or a virtual environment.

In the Teleoperation Environment (T_e) a NASA-JPL Force Reflecting Hand Controller provides the master part, which robustly deals with the Staubli Puma 200 arm which provides the slave part. Proper mapping of positions and forces between master and slave workspaces is handled by the underlying teleoperation framework, see Fig. 1(a). In the direct Hand-object Manipulation condition (H_m) a Sensable Phantom Omni is used as pointer-tool and for position logging, see Fig. 1(b). In the Virtual Environment (V_e) the force feedback is handled by a MPB Freedom 7S force-feedback haptic device, see Fig. 1(c). For the visual rendering of V_e we use a 22-inch wide screen monitor, placed in front of the subject. The visual scene is generated using the OpenGL library.

A total of 10 participants have been examined (age range from 23 to 36). The first 9 participants have been recruited within our staff; the latter one was a specialty surgeon, with more than 5-years daily experience in laparoscopic surgery. They were not informed of the experimental goals and were simply instructed to carry out the task. All the participants have a normal sense of touch and have used their dominant hand to perform the task. Before each task, a short training session allows the user to get familiarized with the experimental conditions.

Task I: Stiffness Perception

The aim of this task is to measure the perceptual capabilities in stiffness discrimination in a teleoperation environment (T_e) as well in a virtual one (V_e). Discrimination abilities in stiffness perception are fundamental in any palpation task, and they are strictly related to the efficiency of organs and inclusion recognition. As discussed in Vicentini and Botturi (2010a), we measure the maximum penetration depth, the exerted force, and the amount of time that it takes to retract a tool from a body upon touching it. Subjects are instructed to move along one designated direction - i.e. along the vertical z-axis (close-far) - until they felt the contact. Subjects are asked to softly penetrate inside the pliable surface,

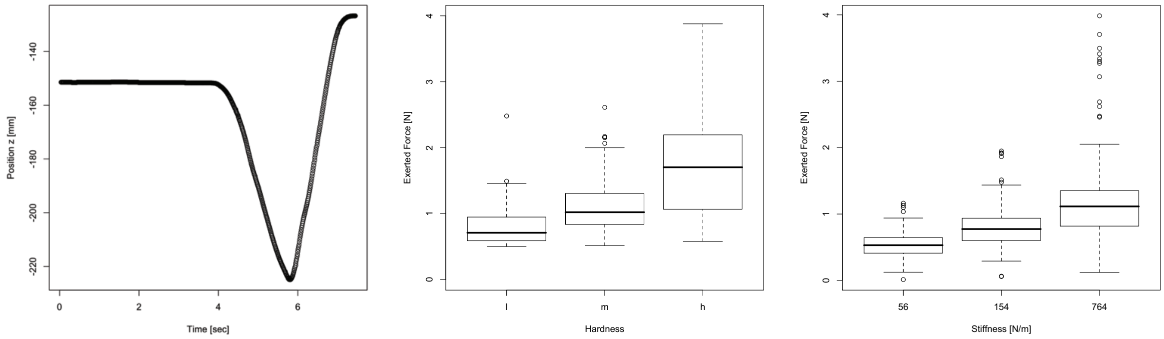

Figure 2: (a) Prototypical motion path collected during T_1. (b-c) Exerted force vs. surface stiffness: l, m, and h refer to low, medium, and high stiffness bodies. Aggregate data show median values, and interquartile ranges.

to feel the contact and to immediately retract the probe, by minimizing the exploratory time and the penetration depth.

Soft tissues with different stiffness were involved as stimuli in the teleoperation setup. Solid blocks of different stiffness were built using gel wax with the addition of different percentage of paraffin (none, 8%, and 16%). The stiffness value of these objects was measured, and it was found to be, respectively, 111, 308, and $1517 N/m$.

The randomized factorial design includes two experimental conditions: teleoperation tapping of three pliable objects, and tapping of virtual objects characterized by the same stiffness of the previous ones. In condition V_e, the stiffness of the virtual objects was fixed to the one measured in the previous experiment. Objective measures are: reaction time, force exerted, and overshoot error. Starting from these measures, we identify the perceptual capabilities in tapping, and we compare the performance collected by the same subjects in the two experimental conditions.

Results

Fig. 2(a) shows a prototypical motion path. Subject moved toward the virtual surface at a constant velocity, which did not change after the contact with the virtual surface. It is possible to observe how a clear movement in the opposite direction begun when the surface was perceived.

As shown in Fig. 2(b-c), average exerted force in T_e for the low stiffness body was 0.71 N (interquartile range IR between 0.59 and 0.95 N); for the medium one it was 1.02 N (IR 0.84 to 1.31 N); for the harder one it was 1.70 (IR 1.07 to 2.20 N). In V_e it was 0.53 N (IR 0.41 to 0.64 N); for the medium one it was 0.77 N (IR 0.60 to 0.94 N); for the harder one it was 1.11 (IR 1.82 to 1.35 N). A Repeated-Measure Analysis of Variance (RM-ANOVA) was conducted, to determine if there were significant differences in maximum penetration force values. In both conditions the factor stiffness was highly significant (in T_e $F_{2,303} = 141.73$, and in H_m $F_{2,330} = 101.36$, $p < 0.0001$), as well the factor subject (respectively $F_{8,303} = 31.74$, and $F_{9,330} = 37.96$, $p < 0.0001$). The Tukeys Honestly Significant Difference post-hoc test was used to identify which cluster means was significantly different from others. It showed that penetration forces differ for all combinations of the factorial design. Similar results were found for both dependent measures Penetration Depth and Reaction Time.

	22 mm	24 mm	27 mm	30 mm
22 mm		28.57	11.59	13.04
24 mm	71.43		17.65	10.00
27 mm	88.41	82.35		20.00
30 mm	86.96	90.00	80.00	

(a)

	22 mm	24 mm	27 mm	30 mm
22 mm		43.57	0.00	5.56
24 mm	56.25		0.00	15.38
27 mm	100.00	100.00		8.33
30 mm	94.44	84.62	91.67	

(b)

Table 1: Judgments on couple comparisons: (a) shows the percentage of correctness on couple comparison for condition V_e, with 7 repetitions. In the lower left corner the corrected ones, in the top right the wrong ones. (b) the same data for H_m, with 3 repetitions.

Discussion

We observe that the results collected in the virtual environment (V_e) and the teleoperation scenario (T_e) are comparable, therefore we can conclude that a virtual environment let a user to feel the perceptual experience as in a teleoperation environment.

Task II: Size Discrimination

This second task is aimed at identifying the human capabilities in size discrimination. As discussed in Tan, Pang, and Durlach (1992), the object size is a very relevant dimension while exploring multiple objects in a haptic only environment.

We randomly present to each subject pairs of objects, for several repetitions. We involve simple solid block objects, with a square base with different side size: four levels, 22, 24, 27, and 30 mm. These objects are realized both in a quasi-rigid material (i.e. wood), anchored on the experimental surface, and virtually rendered. Subjects are asked to judge the biggest one. The factorial design includes 2 experimental conditions: exploration of the objects properties with a direct hand-object manipulation (H_m), and in the virtual simulator environment (V_e). The task is carried out blindly: i.e. during the test in the real environment the subject does not have visual feedback, whereas in virtual environment a blob, larger in size than any object, gives a rough hint about stimulus position.

Objective measures collected during each trial are: exploration time and order judgment. Starting from these judgments, we identify an order relationship among stimuli. We test the discrepancy between a physically true matrix and the observed matrix, and whether there are different among the factorial conditions.

Results

We verified whether there is no significant difference among the stimuli presentation as concerned with the objective measures covered distance and exploration time. That is, we assume no learning effects due to the kind of task and the subjects' expertise. As depicted in Fig. 3, we observed how the trial number is not a significant predictor nor for the covered distance ($F_{6,415} = 0.19$, $p = 0.98$) nor for the exploration time ($F_{6,415} = 0.40$, $p = 0.88$). These results justify the assertion that for expert subjects there is no significant learning effect in size discrimination tasks.

As shown in Table 1, it is possible to observe that the percentage of correctness in size discrimination between couple of objects is always high. This is a relevant result, from which we can affirm that subjects show a discrimination threshold below 10% for

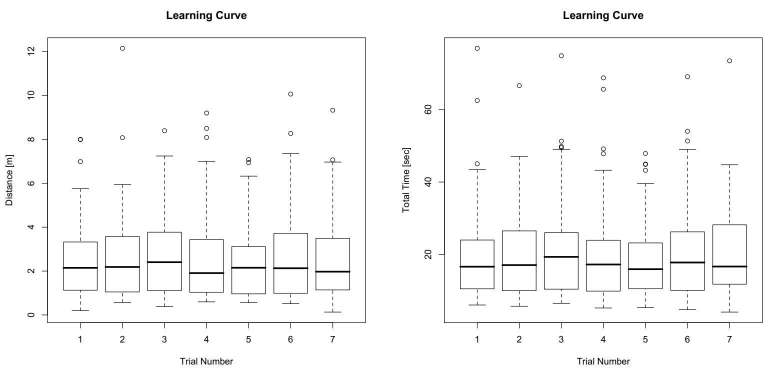

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Figure 3: Learning Curve Analysis: Trial number versus covered distance and exploration time for aggregate data

size between 20 and 30 mm, both in virtual environment (V_e) and in direct hand-object manipulation (H_m). That is, the percentage of correctness is over such point which in general is considered as the upper bound of the point of subjects equality.

By fitting the cumulative responses to stimuli presentation we have estimated the function which describes the probability that participants judged a stimulus as exceeding the standard stimulus (here 22 mm). In order to identify the psychometric function and its parameters, we fitted the logistic function using a Maximum Likelihood estimator.We estimate a JND in size discrimination equal to 10.9%.

Discussion

The ability to correctly discriminate objects characterized by different size is well achieved in a sole haptic scenario: both in a virtual environment and in a direct hand-object manipulation. We identify a size discrimination threshold consistent with the results reported in the literature: Tan et al. (1992) found that the JND is 8.1% for length equal to 10 mm; Durlach et al. (1989) observed a JND of 1 mm for the same reference length.

General Discussion

In these experiments we have accounted for user capabilities to inspect an object by discriminating its stiffness and size. Each task was evaluated according to different experimental haptic conditions. Psychophysics methods were employed to investigate the relationships between experimental factors, such as contact velocity, environmental stiffness, presentation order, as well as their effects onto force threshold and reaction time. The results collected in the surgical teleoperation setup did not differ significantly from the ones collected in real hand-object manipulation, nor in virtual environment. These results should be considered as a proof of the transparency achieved by the developed virtual environment for surgical training (Lawrence, 1993). In all the tasks, we do not observe significant differences between staff and surgeon exploratory behavior. That is, the performance achieved by the surgeon during these benchmark did not significantly differ from the ones collected within the staff. At first, it may be considered as a relevant result: a surgeon did not feel unusual its exploratory behavior nor in the virtual nor in the teleoperation environment. Besides, it also could mean that with the proposed tasks we did not assess specific surgical skills for robotic surgery, but common human skills in object identification and discrimination. Even the training cannot change the results of the contact perception: even expert users do not change the main stream.

These results can be appreciated in the context of developing virtual scenarios for surgical simulation. Such applications demand increasingly complex haptic virtual environments and suitable modeling. For this reason, the haptic interaction with pliable object has to be modeled according to several key factors: velocity of motion, reaction time and posture (Vicentini & Botturi, 2010a). In designing one such environment, it is crucial to be aware of the dependence of rendering parameters, especially if it can result in distorted perception of organ properties.

Our findings emphasize the role played by perceptual capabilities in activities such as the ones involved during a palpation task, i.e. haptically touching a virtual organ with a probe for stiffness, size and position detection and discrimination.

Further work is needed to establish standards for assessment methods and performance levels for robotic surgery. Although there is an international consensus that measurement must have good measurement properties, only general guidelines are actually available, and there are no comprehensive criteria for what constitutes good measurement properties in robotic surgery. Without clear standards the evidence-based selection of measurement instruments is strongly hampered. In the experiments here proposed we considered the user capability of distinguishing between textures of tissues characterized by different roughness. These benchmarks are going to establish a continuum between the training and teaching set-up, the preoperative planning phase, and the actual surgical procedure.

Acknowledgments

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