Human Factors in Haptic Contact of Pliable Surfaces

Abstract

This paper considers relevant human factors to interact with a pliable body in a teleoperation surgical environment. Our aim is to identify the human capabilities, in terms of penetration depth and responsiveness, in a task of pliable surface contact, where surgeons are required to adopt a specific behavior immediately after the contact. A psychophysical experiment is conducted using virtual surfaces rendered with two different force-feedback devices. The results show that impact velocity affects performance in surface contact perception. In a second experiment where different postures are used, we examine whether the previous results hold for the particular ergonomic configuration employed. The results show that posture affects performance especially in expert users. Our findings underscore the importance of understanding the interplay of human perceptual parameters in the surgical teleoperation framework.

1 Introduction

The human perceptual capabilities related to a surgical teleoperation scenario are not well known. Such studies are important for improving the transparency of the telemanipulation system, for safety improvement, for the design of virtual reality simulators, and for the specification of augmented reality applications that overcome perceptual and cognitive limitations (Lamata et al., 2008). In this context, this paper presents a study of the amount of time it takes for a surgeon to retract a surgical tool from an organ upon touching it. The reaction time includes the time it takes for the surgeon to detect a collision with the organ, and to initiate a retraction of the surgical tool, given the dynamics of the surgical tool.

In a teleoperated kinesthetic interaction, since the surgeon lacks direct tactile information, the probe of the haptic device has to penetrate a surface before the user, via force feedback, is able to make use of kinesthetic cues and deduce the features of the organ (Wagner, Stylopoulos, Jackson, & Howe, 2007). The deeper the probe pushes into the deformable body, the higher the contact forces are, and the better the surgeon perceives the body’s physical characteristics. However, especially in a surgical task, it is necessary to achieve a compromise between accuracy in tissue discrimination, governed by the magnitude of force feedback (Cholewiak, Tan, & Ebert, 2008), and the temporal
and displacement extent of surface penetration, which is tightly related to the probability of damaging the tissue (De, Rosen, Dagan, Sinanan, & Hannaford, 2007).

In this work, rather than using a full teleoperation setup, we represent the slave side as a virtual environment and assume an idealized teleoperator with perfect tracking position, perfect force reflection, and negligible time delay. The experimental setup is such that forces are only applied in the normal direction of a surface (i.e., there is no shear component to the force vector).

In the remainder of this paper, the experimental goals are introduced in Section 1.1. The results on force detection thresholds in haptics are reviewed in Section 2. In Section 3, the experimental setup is described. In Sections 4 and 5, the two experiments are described. A discussion on the results and further developments are reported in Section 6.

1.1 Experimental Goals

Our goal is to measure the maximum penetration and the latency time required for a surgeon to reliably perceive the haptic collision with pliable surfaces, and to retract the haptic tool by actively commanding his or her muscles. During this amount of time, we consider the maximum penetration depth of the tool inside the human body’s internal organs.

We expect to define human perceptual capabilities with respect to touching bodies characterized by low stiffness values (i.e., the values reported for human epidermis, from about 80 to 400 N/m; see Gerovich, Marayong, & Okamura, 2004). How deep does a virtual probe have to penetrate before contact with a virtual surface is felt and a target behavior is begun? How long does it require? We aim at a better understanding of what happens when the surface stiffness and contact velocity are combined in a factorial design. How is the velocity factor related to perceptual performance in surface touching? How do capabilities vary due to different haptic devices? To what extent do postural conditions affect haptic perception? What is the minimum time required for subjects to voluntarily react to contact forces, regardless of stiffness and velocity?

In order to experimentally address our questions, we employ a surface detection task in which subjects are instructed to halt exploration as soon as they feel the contact with a virtual object and to retract the haptic tool by actively commanding the muscles. In Experiment I, we examine stiffness perception along hand-centered orthogonal Cartesian directions. A virtual environment is implemented to haptically render a virtual body characterized by defined values of stiffness. Different haptic devices are considered. In Experiment II, we examine several postural conditions, to examine whether previous results hold only for the particular ergonomic configuration employed in Experiment I, or can be generalized and considered as representative of human perception.

2 Previous Work

2.1 Stiffness Perception

We consider the problem of the perception of the surface reaction force on penetration overshoot following the Gibson (1962) perspective of active touching as an exploratory sense. When we examine an object using the sense of touch, the cutaneous sense provides an observer with information about stimulation of the skin surface, whereas kinesthesia provides static and dynamic information about the relative positioning of the effectors used in touching. When a tool is held in the hand and it is already in contact with an object, the softness of the object can still be discerned by actively pressing the tool into the object. During active touch, kinesthetic information about the position and movement of joints, muscles, and skin, in addition to knowledge of central efferent commands, provide useful cues that allow the observer to discriminate differences in object compliance unconfounded by differences in applied force and velocity (O’Malley & Goldfarb, 2002).

Resistance to active touch is perceptually ascribed to the existence of a surface defined by certain physical characteristics, among which is stiffness (i.e., force per deflection). For the special case of unconstrained uniaxial compression, it is possible to implement a general method to render a resistance force $F_p$ that opposes the
penetration depth $D$ by a proportionality coefficient $k$, the stiffness. Presumably, perception of stiffness $k$ is based on the perception of both force and displacement. It is unknown whether there exist dedicated stiffness sensors in the peripheral sensory organs, but human behavior nevertheless hints at the presence of displacement and force sensors.

Several studies have particular relevance for quantitative measurement of human stiffness perception. Jones and Hunter (1990) and Dhruv and Tendick (2000) measured the differential threshold for stiffness, that is, the minimum difference between the stiffness values of two surfaces that leads to a change in the perceptual experience. Shon and McMains (2006) considered stiffness values in the range of 1000 to 4000 N/m, and reported an overshoot error, defined as the length between crossing a sharp edge and regaining control of the movement, from 3 to 13 mm, that decreased with increasing stiffness. O’Malley and Goldfarb (2002) evaluated simulation quality in terms of perceived versus actual surface stiffness. They observed that on average, a user is able to correctly identify size differences of a 7 mm width with 90% accuracy when considering surface stiffness values above 400 N/m. Besides, they reported that higher values of stiffness do not significantly enhance the subjects’ size discrimination performance. In an additional study, O’Malley and Goldfarb (2004) reported that subjects reached a limit in their perception of detail (identification, detection, and discrimination of round and square cross section ridges) at a maximum stiffness level of 300 N/m. Upperman, Suzuki, and O’Malley (2004) found comparable results with a lower range of stiffness values (as low as 100 N/m). Their findings indicated that haptic interfaces are capable of conveying significant information to users at fairly low levels of virtual surface stiffness.

Choi, Walker, Tan, Crittenden, and Reifenberger (2005) focused on the human perception of surface topography when stiffness varied along the surface. They examined user behavior in a task of lateral surface stroking. They analyzed stroking behavior with virtual surfaces, with the declared goal of accurately perceiving surface topography. They found that penetration depth $D$ varied with surface stiffness $k$, in such a manner that penetration force $F_p$ remained constant:

$$ D = \frac{F_p}{k} \quad (1) $$

They concluded that subjects tried to maintain a constant penetration force in their haptic exploration patterns. Their findings led them to formulate the so-called force-constancy hypothesis, which states that users maintain a constant penetration force while exploring haptic virtual surfaces.

The aforementioned studies considered generic exploratory patterns and did not take into account related parameters such as contact velocity, reaction time ($RT$, i.e., time required for the subject to perceive contact with the body and react with a well-defined behavior), postural conditions, or muscle impedance.

### 2.2 Relevant Human Factors

Several studies have stressed the role of motion speed as a key factor in haptic tasks. Taking velocity into account is helpful in better quantifying the precision of force control, as well as allowing for the identification of upper speed bounds for people to control a constant force. In a task of tactile letter recognition, Vega-Bermudez, Johnson, and Hsiao (1991) found an average scanning velocity of 17 mm/s. Scanning velocity between 20 and 40 mm/s had no significant effect on performance, while faster speeds up to 80 mm/s yielded a significant decline in object identification. In a force control task using a reference speed factorially varied from 1 to 30 mm/s, Wu, Abbott, and Okamura (2005) determined the optimal bound of finger force control ability to occur at a velocity of 20 mm/s. Moreover, they found that performance decreased as the velocity of finger motion increased. Recently, Yang, Bischof, and Boulanger (2008) considered the relevance of hand speed and direction of motion on force detection thresholds. They found that hand movement impairs the perception of force magnitude. Their results showed no significant difference between the discrimination thresholds for fast (28 mm/s) and slow (14 mm/s) hand movements.
In haptics, only a few studies have taken into account RT in recognition tasks. Smeets and Brenner (1994) used an RT paradigm to assess the extent to which motion detection depends on relative motion. In a discrimination task, they found that RT is inversely related to contact velocity. In addition, they showed that RT can be seen as the sum of a stimulus-independent latency time $RT_0$ (required for neural transmission) and the time it takes to cognitively process the stimulus. They reported a time delay compounded by a velocity-independent processing time ($RT_0 = 194 \text{ ms}$) and by the processing time required by the cognitive function for detecting the relative contact speed. In a task of haptic recognition, Klatzky and Lederman (1995) found that it takes about 300 ms to touch an object and immediately perform a specific behavior. Furthermore, they found that response time in haptic tasks is not strongly related to learning effects: response time is not significantly affected by presentation order or by the number of trials. In a tapping task of virtual objects with values of stiffness between 200 and 1,020 N/m, Kuchenbecker, Fiene, and Niemeyer (2006) built a transient penetration-based feedback force that took into account an RT of approximately 150 ms. Experimental tests showed that adding such transients improved the perception of contact with a virtual object.

As LaMotte (2000) and others have shown, particular exploratory procedures are optimal for extracting information about specific stimulus properties. For example, applying static pressure to a surface provides information about hardness. He also suggested that a key variable is the rate of pressure increase, which in turn depends on changes in both force and contact area. When subjects actively tapped or pressed the compliant objects, they discriminated softness as well by means of a stylus as they did by contacting the objects directly with a fingertip. Discrimination with the stylus was unaffected by whether the stylus was controlled by one or more fingers.

Rossetti, Meckler, and Prablanc (1994) reported that accuracy in localization by pointing was enhanced in comfortable postures and degraded in uncomfortable postures that use extreme joint positions (wrist flexion, shoulder elevation, or both). Their results showed an increase in pointing variability when extreme joint postures are used. Balakrishnan, Wavefront, and MacKenzie (1997) showed that the pen-hold posture does not necessarily perform better than other segments of the upper limb (i.e., wrist, forearm). Dhruv and Tendick (2000) pointed out that subjects may be able to change their sensitivity to an object’s stiffness by changing environment exploration strategies or limb postural conditions. More recently, Israr, Choi, and Tan (2006, 2007) reported variation on force detection threshold due to the grasping posture involved when using different force-feedback devices.

In the following sections, we investigate the factors that affect the performance on a pliable surface contact task, such as contact velocity, reaction time, hand grip, and haptic device.

### 3 General Methods

In this section, we describe the experimental setup for our experiments. Additional specific details are presented along with the corresponding data.

#### 3.1 Apparatus

Two commercially available haptic devices were used in rendering the virtual surfaces: a Freedom 7S force-feedback device (MPB Technologies Inc., Montreal, Quebec) and a PHANToM Omni force-feedback device (SensAble Technologies, Inc., Woburn, MA). The Freedom 7S is a high performance device (Hayward, Gregorio, Astley, Greenish, & Doyon, 1998) with a position resolution of 2 μm and a force resolution of 40 mN. The update and log rate was $> 2 \text{ kHz}$. The PHANToM Omni is a cost-effective, easy to use haptic device (Sensible Technologies Inc., 2008) with a position resolution of 55 μm. The update and log rate was 1 kHz.

The devices were placed to the right of a 22-in wide-screen monitor placed in front of the subject (see Figure 1). The base of each device was positioned so that it could be comfortably reached with the subject’s dominant hand. A pen-hold grasping configuration was re-
quired by concurrently using the thumb, index, and middle fingers. The hand operating the device was not anchored to the desk, hence neither the wrist nor the elbow was provided with a grounded support.

### 3.2 Stimuli and Procedure

The visual scene for our experiment was generated using the OpenGL library and displayed, as shown in Figure 2, on the monitor. A small red circle acted as a proxy for the position of the stylus tip in the virtual world. The haptic stimulus consisted of a virtual surface, placed 80 mm away from the initial position of the red circle. The virtual surface was not visually rendered, so as not to bias the subject with respect to the location of the surface contact point. Subjects were instructed to move along one designated direction, that is, along the vertical \( z \) axis (close-far), or along the \( y \) axis (up-down) until they felt the surface (see Figure 1). Only the motion along the designated direction was visually and haptically rendered. When the tip penetrated the virtual object, force was rendered according to

\[
F_p = -k \cdot d
\]

In implementation, how to measure the force \( F_p \) delivered to the subject’s hand was an important issue. Using a dedicated force sensor and/or an accelerometer could verify the accuracy of the haptic device in force rendering, almost certainly accounting for the haptic interface dynamic measurement errors. But this would have increased the cost and the complexity of the system. Instead, we relied on the calibration process and control algorithm provided by the device manufacturers, based on the joint angle sensors (usually optical encoders) and the motor dynamics.

In order to provide a reference for the velocity of the hand motion, a virtual yellow circle was initially placed in the same position as the red marker; as soon as hand motion was detected, the reference moved along the target direction with constant velocity \( v_c \). Subjects were asked to move the red circle at the same velocity as the yellow circle, until they felt the contact with the virtual surface; once contact was perceived, subjects were in-
structed to instantly stop their motion and move backward as soon as possible.

Direction, stiffness, and reference velocity were manipulated in a three-factor full factorial design. Maximal penetration depth ($D$), contact velocity ($v_m$), and $RT$ were measured as dependent variables. $RT$ was here defined as the time required to subjectively perceive the virtual surface once it had been reached, to stop the penetrating motion, and to begin an opposite movement. It was measured as the time between the beginning of force rendering and the maximum penetration inside the surface.

### 3.3 Statistical Analysis

Statistical analyses were conducted separately for each subject and for aggregate data. Every group analysis included a factor for individual subjects so that differences between subjects were not counted as random variation. This made each analysis more sensitive to the stimulus parameter being varied.

### 4 Experiment 1

The purpose of this experiment was to estimate the maximum penetration depth and the amount of time that it takes to retract a tool from a body upon touching it with different haptic devices. In order to investigate whether the threshold depends on surface stiffness and on contact velocity, different values for $k$ and $v_c$ were used. We were also interested in evaluating the relevance of the perceptual findings upon devices that span the cost spectrum, supposing that the cost of a device is correlated with the fidelity in force rendering.

#### 4.1 Participants

A total of 10 males and two females (age range from 23 to 33) were tested with the Freedom 7S device, and five males and two females (age range from 26 to 32) with the Omni device. The participants were recruited by word of mouth within the staff of the ALTAIR laboratory of the University of Verona (Italy). 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 used their dominant hand to perform the task. During each experimental session, white noise was presented through the ears of the subjects.

### 4.2 Procedure

The following levels of the factors stiffness and velocity were involved. Four stiffness values were chosen among commonly reported values for the human body: 80 N/m (for a soft surface, similar to human fat), 120, 160, and 320 N/m (for a relatively harder surface, similar to human skin or muscle tissue). We used three different values as reference for the contact velocity $v_c$ (10, 20, and 30 mm/s). The first value corresponds to very slow motion, whereas the last is considered to be above the upper bound of hand force control ability (Wu et al., 2005). We considered the motion along the $z$ axis in the close-far hand movement direction.

Combinations of experimental parameters were tested in random order for 20 repetitions each. Each experiment took about 70 min. The subjects took a break every 15 trials and whenever fatigue occurred. All the participants were given 36 practice trials before actual experimental data were recorded.

### 4.3 Results

#### 4.3.1 Penetration Depth

For each trial, penetration depth, velocity, and acceleration were logged for data analysis. Figure 3 shows a prototypical motion path. Figure 3 shows that the subject moved toward the virtual surface at a relatively constant velocity, which did not change after initial contact with the virtual surface. It is possible to observe how acceleration varied just before the maximum penetration inside the surface is reached at $RT$. From this point, a clear movement in the opposite direction was begun.

The results are shown in Figure 4. With the Freedom device, the average penetration depth was 4.08 mm (interquartile range IR between 2.47 and 5.29 mm). With
the PHANToM device, it was 3.50 mm (IR 1.75 to 4.63 mm).

Data collected from each subject were analyzed to test whether the minimal penetration depth depended on stiffness and on contact velocity. We employed a repeated-measures analysis of variance (RM-ANOVA) to determine whether there were significant differences in penetration depth values due to the factors of stiffness, velocity, and device. In addition, the Tukey’s honestly significant difference (HSD) post-hoc test was used to identify which cluster means were significantly different from others. The third-order interaction between velocity, stiffness, and device was significant \[ F(6, 4516) = 3.361, p < .01 \]. The first order factors were highly significant [speed: \( F(2,4516) = 380.451, p < .0001 \); stiffness: \( F(3,4516) = 1,157.590, p < .0001 \); device: \( F(1,4516) = 142.656, p < .0001 \)]. Moreover, the HSD test showed that the penetration depths were always different in the factorial design. It is possible to conclude that stiffness and velocity were two independent significant predictors of the penetration depth.

In Figure 4, we also plot penetration depth versus stiffness. The data clearly show that penetration depth decreased as surface stiffness increased, for all subjects. The IR followed the same decreasing trend, indicating that the surface detection task was easier when the surface was stiffer. A similar trend was ob-

Figure 3. Prototypical data for the contact task: (a) measured position, (b) rendered force, (c) velocity, and (d) acceleration are plotted against time. Solid lines refer to the surface contact point. The first and second dashed lines refer to RT and to the total time inside the surface RT\textsubscript{tot}, respectively. The dot-dashed line refers to the time at which the target behavior is begun.
served between penetration depth and contact velocity: the faster the motion, the more delayed the surface detection.

Note that the haptic devices had a relevant role in minimizing the penetration depth inside the virtual surface. As observed elsewhere (Salisbury, Gillespie, Tan,}

Figure 4. Penetration depth plotted against contact velocity and surface stiffness. Data are collected with (a) Freedom 7S and (b) PHANToM Omni devices. Aggregate data show median values and interquartile ranges (lower bound, first and third quartile, upper bound).
Barbagli, & Salisbury, 2009), device cost is not always a clean indicator of its ability to properly render forces. Although a similar trend can be observed between the two devices, the minimal penetration depth was observed with the lower-profile device (the Omni), and not with the higher-performance, higher-cost device (the Freedom 7s).

4.3.2 Penetration Force. In Figure 5(a), penetration force is plotted against speed for aggregate data, showing a linear fan pattern. A multiplying relationship between velocity and stiffness was observable for both devices: penetration force increased with both surface stiffness and impact velocity.

With the Freedom device, the average penetration force was 0.57 N (IR 0.41 to 0.72 N), whereas with the Omni it was 0.48 N (IR between 0.31 and 0.60 N). An RM-ANOVA was conducted to determine whether there were significant differences in maximum penetration force values. The interaction between velocity and stiffness was statistically significant \[ F(6,4516) = 9.627, p < .001 \], as well as the third order factor \[ F(6,4516) = 2.218, p < .05 \] and the first order factors [speed: \( F(2,4516) = 473.573, p < .0001 \); stiffness: \( F(3,4516) = 118.630, p < .0001 \); device: \( F(1,4516) = 216.887, p < .0001 \)]. Moreover, the HSD test showed that penetration forces differed for all combinations of the factorial design. It is possible to state that contact velocity can provide acceptable fit indexes in accounting for data variability.

4.3.3 Reaction Time. The analysis of the reaction time \( RT \) led us to consider a further relevant factor. With the Freedom device, the average \( RT \) was 380 ms (IR between 263 and 471 ms). With the Omni, it was 365 ms (IR between 253 and 435 ms). As for the previous dependent measures, the third-order interaction among device, stiffness, and velocity was significant \[ F(6,4516) = 5.168, p < .001 \].

In Figure 5(b), \( RT \) is plotted against contact velocity for aggregate data. The \( RT \) decreased as surface stiffness increased, and the IR followed the same decreasing trend. This result was likely rooted in the higher forces rendered in correspondence to higher values of stiffness.

**Figure 5.** (a) Penetration force and (b) reaction time \( RT \) are plotted against contact velocity; aggregate data from the two devices. Dashed lines represent different stiffness values. The figures show median values and interquartile ranges (lower bound, first and third quartile, upper bound).
Subjects halted motion when they experienced a certain perceivable force $F_{\text{p}}$, that is, the smallest detectable level of a stimulus in a certain task.

To the best of our knowledge, a result that has not been considered so far is that $RT$ also decreased as the velocity $v_{\text{m}}$ increased, according to an inverse relationship governed by a constant, $c$ (see Smeets & Brenner, 1994, p. 193). In addition, $RT$ asymptotically converged to a stimulus-independent time $RT_0$, which could be interpreted as the minimum time required for neural transmission and cognitive processing (see Flanders, 2009). We can interpret $RT$ as a function of velocity according to

$$RT = RT_0 + \varepsilon \cdot v_{\text{m}}^{-1}$$

and yield an estimate for $RT_0$ by fitting the data with a least-squares (LS) criterion. For aggregate data, our estimate $RT_0 = 218$ ms is close to the values reported elsewhere (Schmid & Bekey, 1978; Smeets & Brenner; Flanders).

This result provides insight into the human capabilities in a task of surface detection: regardless of the compliance of the body and of the exploratory velocity and forces, within the first 200 ms it is not possible to haptically perceive contact with a virtual body, to cognitively elaborate the perception, to overcome the device inertia, and to elicit an appropriate behavior. Besides, changing the contact velocity can effectively vary the effective $RT$.

### 5 Experiment 2

The second experiment took into account different grasping and postural conditions in order to verify whether the previous findings on haptic perception were related to a specific ergonomic configuration, or to a defined movement direction.

#### 5.1 Procedure

We considered several grasping and postural conditions apart from the one involved in the just mentioned experiment on stiffness detection. The involved grasping conditions were based on the different grasping of the in-use surgical tool for virtual or real environments.

We considered only the Omni haptic device, since it had shown the better performance in surface perception by minimizing the penetration depth. With respect to the procedure discussed for Experiment 1, we introduced two further independent variables: posture and movement direction.

We evaluated five postural conditions by varying how the haptic device is held. As illustrated in Figure 6, we took into account the following levels for the factor posture: (a) pen-hold posture, (b) wrist comfortably resting on the desk, (c) wrist brace firmly avoiding wrist movements, (d) stylus vertically held in vertical fist between thumb and the other fingers, and (e) stylus vertically held in horizontal fist between forefinger and middle finger. We defined these conditions in order to consider the role of the wrist (conditions a, b, and c), the inclination of the hand (condition d), and the wrist flexion (condition e).

The five postural conditions were factorially combined with three designed directions (i.e., up-down, along the vertical $y$ axis; right-left, along the horizontal $x$ axis; close-far, along the $z$ axis, see Figure 1), and three stiffness values (80, 160, and 320 N/m). For this experiment, we adopted a unique reference velocity (20 mm/s). In order to take into account the reduced workspace for conditions b–d, the virtual surface was placed at a position $l$ that differed among trials, randomly chosen between 30 and 40 mm from the initial position of the haptic device. In this way, the hand had to produce a smaller movement along the designed direction.

Within the factorial design, the postural conditions were presented according to a Latin square. For each postural condition, the nine combinations of direction by stiffness values were presented in a random order to each subject with 20 repetitions. Each experiment took about 45 min, with short breaks every 5 min to reduce fatigue. All the participants were given a 5 min practice session before beginning.

#### 5.2 Subjects

Ten subjects (age range from 24 to 33 years; seven males and three females) took part in this experiment.
Subjects were not informed of the experimental goals and were simply instructed to carry out the task. All the participants had a normal sense of touch.

In terms of their prior experience with force-feedback devices, three participants were expert users who used force displays regularly for their research. Three subjects were generally familiar with haptic interfaces but were not as experienced with the haptic device as the expert users. The others had not used any haptic interface before they took part in the experiment.

5.3 Results

As was done in the previous experiment, RM-ANOVA was conducted to determine whether there were significant differences among the involved factors. The results are reported in Table 1.

A similar behavioral pattern was observed: penetration depth decreased as surface stiffness increased. Figure 7 illustrates the penetration depth according to expertise levels and postural conditions. It clearly emerges how the expert subjects always perceived the virtual surface with the lowest penetration depth, especially for lower values of stiffness. Differences due to the postural conditions were observed only for intermediate and novice subjects.

5.3.1 Subjects’ Expertise. We accounted for differences among the participants’ skills with the HSD test. The multiple comparisons of penetration depth means confirmed significant differences among the subjects’ expertise. That is, the paired comparison of the means of these levels revealed that the linear hypothesis $|x - y| = 0$ was not accepted where $x$ and $y$ were the
expertise levels. Expert users differed from intermediate and novice ones of 0.61 and 1.61 mm ($t$-value 7.28, adjusted $p$-value <.001, and $t = 20.61$, $p < .001$, respectively). Also, the average difference 1.00 mm between intermediate and novice was significant ($t = 12.81$, $p < .001$). Expert users had average penetration depths of 3.30, 2.06, and 1.24 mm for stiffness values of 80, 160, and 320 N/m, respectively. Intermediate users showed values of 4.75, 2.63, and 1.66 mm, while novice users reported 5.14, 3.15, and 1.93 mm. This finding was consistent with Choi et al. (2005) who reported different exploratory behaviors according to the subjects’ expertise.

5.3.2 Postural Conditions. Differences among postural conditions changed according to the differences in expertise. For expert and intermediate users, minimal penetration values were observed for conditions $d$ and $c$. That is, the average values of penetration depth for conditions $b$, $d$, and $e$ were always higher than the ones of conditions $a$ and $c$. Different results were observed for novice users. For these participants, the worst condition in penetration depth was $a$. No significant differences were reported among the other conditions.

Table 2 reports the group means and standard deviations for the observed data (penetration depth, penetration force, and RT). Data are pooled according to postural conditions and involved directions. Although the postural conditions $a$ and $c$ gave minimal values in terms of overshoot effect, these results could be obtained only by those users with specific expertise. Conversely, condition $a$, which allowed expert conditions.

Table 1. Results from the ANOVA Test Conducted for Aggregate Data Collected in Experiment II for the Dependent Measure of Penetration Depth

<table>
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<th>Factors</th>
<th>DOF</th>
<th>$F$ value</th>
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*Factors and their interactions, degrees of freedom (DOF), $F$ value, and associated $p$ value are reported. Differences among repetitions and subjects were not counted as random variation, but were specified as error strata.
users to obtain optimal results, was less intuitive for the untrained users. However, the remaining postural conditions, even if unusual or uncomfortable, allowed for penetration depth performance comparable to performance in condition \( a \).

5.3.3 Movement Directions. Significant differences in penetration depth were observed among the movement directions. The penetration depth was always lower along the \( x \) axis (movement right-left) than along the \( y \) and the \( z \) axes (\(-0.39 \) and \(-0.16 \) mm, \( t \)-value \(-2.49 \) and \(-6.09 \), adjusted \( p \) value .034 and < .001, respectively).

As reported by different studies (Samur, Wang, Spaelter, & Bleuler, 2007; Vicentini, De Maggio, Botturi, & Fiorini, 2007), it is likely that subjects had systematic distortions and privileged directions in the ability to perceive forces, especially in near peripersonal space. Differences in penetration depth along the left-right direction were addressed with internal representation of the proximal stimulus as in the case with the position amplitude JND in prior literature (see, e.g., Craig, 1974).

5.3.4 Reaction Time. As far as \( RT \) was concerned, our findings indicated that the same performance was achieved by all the postural conditions. That is, the observed differences among the postural conditions were not statistically significant.

\( RT \) in stiffness detection significantly changed among the designed directions. It was always lower along the \( z \) axis (movement close-far) than along the \( x \) and the \( y \) axes (51 and 38 ms, \( t \) value 11.55 and 8.49, adjusted \( p \) values <.001, respectively). Starting from these findings, we hypothesized that, in order to gain high performance in user’s reaction times, a movement along the \( z \) axis (movement close-far) was preferred to the other directions.

\( RT \) was also affected by differences in expertise. Expert users usually completed the task 20 and 27 ms before intermediate and novice ones (\( t \) value 3.37 and 4.86, adjusted \( p \) value .009 and <.001, respectively).

5.3.5 Discussion. Experiment II showed that the most relevant predictor in task accuracy was not given
by the postural condition, but by the subject’s expertise, as defined by the number of hours involved with a haptic device.

Furthermore, the direction of the movement was found to be a reliable predictor of the time required to perceive the contact with the virtual surface and to react starting a movement along the direction opposite to the exploratory movement.

### 6 Discussion

In this study, we employed perceptual experiments to investigate the relationships between contact velocity, environmental stiffness, and postural conditions, as well as their effects on penetration force threshold and reaction time.

We modeled the haptic representation of pliable virtual-object properties according to several key factors: velocity of motion, reaction time, and posture. These results can be better appreciated in the context of developing complex virtual environments for surgical simulation. Many applications demand increasingly complex haptic virtual environments (Altomonte, Zerbato, Botturi, & Fiorini, 2008). In designing one such environment, it is crucial to be aware of the interplay among rendering parameters, especially if it can result in distorted perception of organ properties. Our findings also emphasize the role played by perceptual capabilities in activities such as haptically touching a virtual organ with a probe and immediately retracting it.

Our findings showed a minimum difference in the human performance between the two devices involved in the experiments. Contrary to common expectation, the low cost device was a more reliable instrument to feel the contact with the pliable surface in our task. We believe that the differences in usability between the two devices here considered were related to the feeling people got when using the devices. Providing a physical meaning is not a trivial task. In any case, the Omni device is more “drivable” because it is compact and heavy, giving more constraints. Following a straight path along a single direction, the Omni device can help the user concentrate on the touching task. The Freedom device is much lighter, but less drivable due to the many DOFs (6 or 7), which make it difficult to follow a single direc-

<table>
<thead>
<tr>
<th>Table 2. Group Mean (SD in Parentheses) for Data Observed in Experiment II*</th>
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<tr>
<td><strong>Direction</strong></td>
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<tr>
<td>Penetration depth (mm)</td>
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<td>Close-far</td>
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<td>Force (N)</td>
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<td>Close-far</td>
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<td>Reaction time (ms)</td>
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*Data are grouped according to postural condition and direction.*
tion. We expect to have better performance with the Freedom device in an exploratory task where a complex behavior (i.e., a composition of different directions and movement) is needed to experience the environment.

Even the training cannot change the results of the contact perception: with the Freedom device, even expert users do not change the main result. Instead, in the posture experiments, the results from the expert subjects are in line with the conventional belief that greater precision and finer perception of surfaces can be obtained by a precision grip (e.g., pen-hold grasping). According to recent studies (Zhou, Perreault, Schwaitzberg, & Cao, 2008), we argue that differences in posture are especially relevant for expert users demonstrating the importance of training for this aspect. All things considered, we should be able to point out specifications for a new concept haptic device: a pen-hold posture and a dynamic structure that can change due to the task at hand, that is, through a virtual fixture that can fix some degree of freedom in the case of the high performance contact task.

We now envision applying the results obtained in this work in a bilateral teleoperation system with time delay. The idea is to use the RT values in conjunction with a compensation method. We argue that signal manipulation has to take into account not only the network delay but also the perceptual RT and the correlation with the expected reaction/performance of the user. Our future work will concentrate on a new compensation algorithm.

In addition, properties of the human information processing system, which can explain the asymptotic trend of reaction time, need to be carefully considered when predicting the performance of a surgeon as well as any human operator. As stated in prior literature (see, e.g., Schmid & Bekey, 1978; Flanders, 2009), processing reaction time is critical in haptic perception. We acknowledge that the reaction time we have measured cannot be entirely attributed to the human ability to detect a virtual surface. The reported reaction time reflects also the ability to cancel the momentum impulse between the hand and the haptic device, which may not necessarily be related to the detection of virtual surfaces. In this way, the results of these experiments also depend on the involved haptic interface. What happens if we use different models characterized by significantly less friction is an open question.

Application-oriented work will focus on implementing methods that take into account our perceptual findings. The goal is to improve accuracy in the teleoperating surgical scenario. We aim at developing in particular a set of compensation rules, capable of granting higher overall accuracy in perceiving a virtual organ. The overall goal is an accurate simulation of haptic interactions between a surgical tool and a human body.

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**References**


