Whole-Hand Kinesthetic Feedback and Haptic Perception in Dextrous Virtual Manipulation

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***Abstract*—One of the key requirements for a Virtual Reality system is the multimodal, real-time interaction between the human operator and a computer simulated and animated environment. This paper investigates problems related particularly to the haptic interaction between the human operator and a virtual environment. The work presented here focuses on two issues: 1) the synthesis of whole-hand kinesthetic feedback, based on the application of forces (torques) on individual phalanges (joints) of the human hand, and 2) the experimental evaluation of this haptic feedback system, in terms of human haptic perception of virtual physical properties (such as the weight of a virtual manipulated object), using psychophysical methods. The proposed kinesthetic feedback methodology is based on the solution of a generalized force distribution problem for the human hand during virtual manipulation tasks. The solution is computationally efficient and has been experimentally implemented using an exoskeleton force-feedback glove. A series of experiments is reported concerning the perception of weight of manipulated virtual objects and the obtained results demonstrate the feasibility of the concept. Issues related to the use of sensory substitution techniques for the application of haptic feedback on the human hand are also discussed.**

***Index Terms*—Dextrous virtual manipulation, exoskeleton glove, grasping force distribution, haptic perception, kinesthetic feedback, psychophysics, virtual reality.**

I. INTRODUCTION

ONE OF THE key characteristics of a virtual reality (VR) system is the real-time multi-modal sensorimotor interaction between the human operator and a computer-animated environment. Such a natural and intuitive human/computer interaction should involve all the sensory modalities of the human being, not only vision but also the other senses and particularly the haptic sense. The term "haptics" derives from the Greek word "$\alpha\phi\acute{\eta}$," and refers to the sense of touch and how to couple it within a virtual environment (VE). It is usually divided into two sensory modalities (although such a distinct separation cannot be established in a physiological basis due to the variety and complexity of inter- and intra-modal sensory interactions): a) the *kinesthesis*, which includes proprioception, as well as perception of muscular effort, and b) the *tactile sense*, which provides cutaneous information, related to contact between the skin of the human body and the external environment (pressure, vibration, temperature etc.), thus enabling the perception of physical properties such as the surface characteristics of touched objects (texture etc.)

The human hand, with its exceptional dexterity and sensory capacities, constitutes undoubtedly the most versatile "tool" employed by the human being to explore the physical world, and interact with it to acquire useful multidimensional sensory information. The close interconnection between perception and action has led researchers to consider haptics as an "active sense" [17] related to manipulative and exploratory procedures [30]. Integrating such functionalities and skills within a VR system still constitutes a real challenge for researchers and engineers in the field. Enabling a natural, intuitive and dextrous haptic interaction within a VE involves the use of appropriate mechatronic devices (for instance of glove-type) providing both: a) good freedom of mobility for the human hand, and motion measurements for many of its degrees of freedom, and b) haptic (kinesthetic and/or tactile) display on different areas of the human hand. The direct measurement of hand actions, rather than measurement of the motion of a device which the hand is constrained to manipulate, is a basic feature of any system aiming to perform human gestural analysis and recognition. Such systems in general can be grouped under the term of *whole-hand input* systems [44]. However, monitoring the coordinated action of the human hand's individual degrees of freedom must be combined with the application of haptic feedback involving various sensory modalities, in order to empower the direct use of the sensorimotor capacitites of the human hand for an intuitive control of computer mediated tasks.

The work presented in this paper concentrates particularly on designing and evaluating kinesthetic feedback to be "displayed" on the human hand. Such a feedback modality aims to convey haptic sensory cues to the human operator through the application of forces on different parts of the human hand (that is, forces on fingers/phalanges or torques on the joints, constraining the motion of individual degrees of freedom of the hand). We can thus refer to this scheme as a *whole-hand kinesthetic feedback*, based on the application of a force/moment distribution on the human hand. Two important issues related to this type of feedback have to be stressed out.

1) The synthesis of whole-hand kinesthetic feedback must be as *device-independent* as possible. It must incorporate information provided by a continuous monitoring of the human operator manipulative intention, as interpreted by direct hand actions on the virtual world, and must convey pertinent haptic sensory cues depending on the task parameters to be displayed. Constraints related to the mechatronic design and control of haptic devices, should also inevitably be taken into account, but only at the final implementation

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Manuscript received May 5, 2000; revised October 11, 2002 and February 25, 2003. This paper was recommended by Associate Editor W. A. Gruver.

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Digital Object Identifier 10.1109/TSMCA.2003.812600

stage, since they may limit what is actually feasible and what can be displayed to the operator through the haptic feedback channel.

2) The functionality and the perceptual characteristics of the human haptic system must be also taken carefully into consideration for kinesthetic feedback design. Generally speaking, the human sensory system possesses a very important property: a high degree of *redundancy*, which reveals the complexity of the perceptual processes (fusion of multiple sensory cues) performed at the cognitive level [15]. This redundancy, which is a ubiquitous feature of all human (and, in general, biological) sensorimotor processes, is often indirectly exploited in the design of VR interfaces, by the application of *sensory substitution* techniques [41]. As far as haptic perception is concerned, intrasensory interpretation of cues is performed from a variety of afferent sensory signals (mechanoreceptors located on different areas of the human hand and arm, i.e., muscles, tendons, joints, as well as on the skin [35]), which are combined together with some efferent motor command signals to form specific "holistic percepts." A question that needs to be investigated is how the loss of such redundancy in the particular conditions of haptic interaction within a virtual world, may affect the performance for manipulation tasks. Are the haptic feedback cues, provided by the application of torques localized on some individual joints of the human hand, sufficient for the perception of specific physical properties (such as, for instance, the weight of a manipulated virtual object)? An understanding of these issues will allow researchers to enhance haptic feedback technology or find optimum compromises for it.

This paper aims to investigate some of the above mentioned issues. It is structured as follows. The first part (Section II) focuses on the synthesis of whole-hand kinesthetic feedback. This is treated as a force/moment distribution problem on the virtual hand, during direct hand manipulation in a VE. The proposed method is based on the use of a weighted pseudo-inverse for the solution of the nonlinear optimization problem and the computation of feedback forces (or torques) to be applied on individual fingers/phalanges (or joints) of the human hand. The solution takes into account information related to the manipulative intention of the human operator (interpreted by the continuous monitoring of the local deformation of the manipulated virtual object), but also explicitly includes terms related to external virtual manipulation forces. These additional terms can be employed (depending on the task and on the performance of the haptic feedback device) to convey feedback information related to static (e.g., weight) or dynamic (e.g., inertia) physical properties during dextrous, direct hand manipulation of virtual objects.

Human haptic perception issues are studied in the second part of this paper, which presents some representative results from the experimental evaluation of the proposed method. This method has been implemented using an exoskeleton force-feedback glove, developed at the Laboratoire de Robotique de Paris (LRP hand master, [6]). Section III starts with a brief description of this device, followed by an overview of the hardware architecture of the experimental testbed. Some basic notions on haptic perception and psychophysics are then exposed, with the emphasis on methods and protocols used for the experimental evaluation of the system's performance. The forced-choice procedure has been used in the experiments to estimate just noticeable differences (jnd) and Weber fractions. Results for the particular case of virtual weight perception are presented, which demonstrate the feasibility of a whole-hand kinesthetic feedback for the perception of virtual physical properties related to the application of external manipulation forces. The results obtained throughout this section are compared with those reported in literature investigating the characteristics of human haptic perception in the real world manipulation case. These comparisons enable us to evaluate, on a common basis, the performance of the proposed feedback modality, and its practical experimental implementation in various virtual task situations.

II. WHOLE-HAND KINESTHETIC FEEDBACK

A. *Force Display Devices: Brief Literature Survey*

As we have already discussed, haptics is an important dimension of VR systems. Many haptic display devices have been developed and are described in the literature. They can be classified according to criteria related to their mechanical design (serial or parallel kinematic structure, motor redundancies etc.), their dynamic performance (control bandwidth, achievable impedance, maximum load etc.) or even ergonomic factors (such as portability, weight/size, safety issues etc.). This paper focuses on the design and implementation of kinesthetic display in VR systems. The most commonly used force-feedback devices can be grouped in two general classes.

1) General master manipulator arms, with typical examples being the universal master arm from JPL [2], and the MEL master manipulator arm [27]. These systems are more often used in the context of bilateral master-slave teleoperation applications [51]. However, it is stated that such robot manipulator arms can also be employed as generalized force-feedback devices to simulate dynamic force and moment interaction between humans and virtual objects [13].

2) Desktop devices, which include generalized force-feedback joysticks, such as mechanisms with parallel kinematic structure (for instance, Stewart platforms [36]), magnetic devices [4], or pen-based devices (with rigid links [11], cable-driven [29] or hybrid [19]). Two typical examples of desktop devices are the PHANToM "Personal HAptic iNTerface Mechanism" [34], and the device described by Yoshikawa in [52], [53].

Most of these haptic feedback systems demand from the human operator to grasp a motorized handle and perform general whole-arm (or wrist) movements, thus suppressing, or constraining, all the other degrees of freedom of the hand. The human haptic system (upper arm, forearm and hand), however, possesses on its whole more than 28 degrees of freedom (dof). Creating systems that keep track of these dofs, including monitoring individual finger/phalangeal contribution during prehensile/manipulative tasks to study and potentially "exploit" human-hand dexterity and skills, still constitutes a real challenge for researchers in the field of haptics and, more generally, telerobotics. Monitoring individual finger joint motion can be performed using glove-based devices [7] (such as for instance the CyberGlove™ manufactured by Virtual Technologies). These devices are suitable for whole-hand input systems, but provide no force-feedback information on the human hand. Very few force-feedback gloves exist today, due to the difficulties inherent to the development and real-time control of such complex mechatronic devices. Typical examples are the Rutgers master [8], which is a pneumatically actuated device with 4 degrees of freedom (DOF), and the hand-feedback mechanism developed at the Scuola Superiore Santa Anna of Pisa [3]. In the work reported in this paper, a prototype exoskeleton glove device (the LRP hand master [6]) was used to provide kinesthetic feedback on the human hand, as will be described in Section III.

B. Whole-Hand Kinesthetic Display: The Concept

As already mentioned in the introductory section, whole-hand kinesthetic display is based on the application of forces (or torques) on individual fingers/phalanges (or joints) of the human hand. One goal is to support a natural human/VR haptic interaction, enabling the human operator to intuitively perceive simulated physical properties within a virtual world, while maintaining in some extent his/her prehensile and manipulative dexterity and skills. Creating realistic haptic sensations through such a hand-distributed kinesthetic feedback is a very complex task. When performing a general manipulation task, external forces and moments are distributed on all the contact regions between the hand and the manipulated object. Each contact force can be decomposed into two parts: an "internal" and an "external" force component. Internal forces have zero sum, ensuring stable grasping but having no effect on the resultant motion of the object, while external manipulation forces are the ones that compensate for the application of an external wrench [33].

Glove-based haptic feedback on the human hand is usually limited in the application of forces simulating the local deformation of the grasped virtual object (for instance, see [9]). These constitute, in fact, internal grasping forces and can, at most, provide information related to the stiffness of the manipulated object. Additional sensory cues, related for instance to the weight of the manipulated virtual object or to its dynamic interaction within the VE (collision with obstacles etc.), can be supplied only through the appropriate distribution of external manipulation forces on the human hand. This observation forms the basis of our approach, which has thus been called *hand-distributed kinesthetic feedback* [49].

This section focuses on the development of a generalized framework for the synthesis of such a whole-hand kinesthetic feedback. The computation of hand feedback forces is based on the solution of a force distribution problem, and is independent of the dynamic characteristics of the haptic device used. The proposed solution takes into account information related to the manipulative intention of the human operator, as interpreted by a continuous monitoring of the local deformation of the manipulated virtual object. It also explicitly includes terms related to the external virtual manipulation forces, which can convey additional haptic sensory cues related to static or dynamic physical properties during dextrous, direct hand manipulation of virtual objects. Some relative work on feedback of external grasping forces in a two- or three-finger virtual manipulation has been reported in the literature by Howe in [20], and by Hashimoto *et al.* in [18]. In [20], a "slight redistribution" of feedback forces on the thumb and the index of the human hand is used, during a two-finger telemanipulation task, to convey sensory information relative to the slipping of the grasped object from the slave hand. Hashimoto and Buss [18] have also developed a system for dynamic force simulation, using a sensory feedback glove with 10 dof: three for the wrist, two for the thumb, three for the index and two for the rest of the fingers moving as a whole. A similar haptic device has been used by Iwata in [21]. External forces, such as the weight of a virtual object, were applied on the palm of the human operator's hand using a 6 dof mechanism. However, forces applied on the fingers depended once again only on the simulated stiffness of the grasped virtual object.

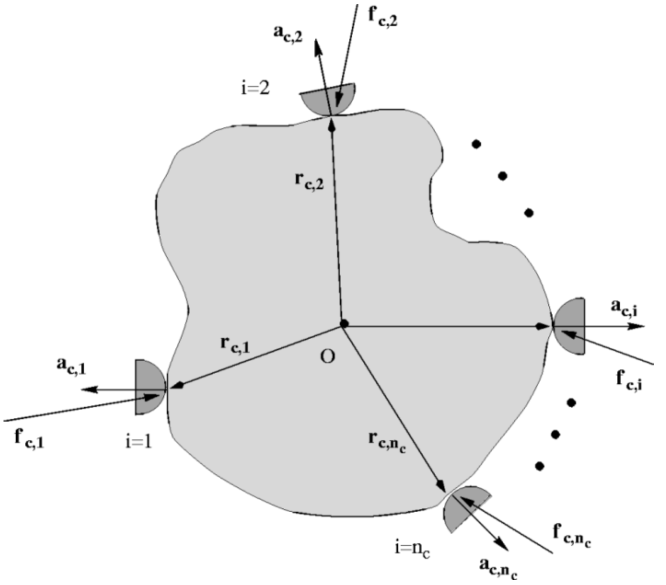


Fig. 1. Grasping of an object with n_c contact points.

C. Problem of Force Distribution on the Virtual Hand

Let us consider grasping of a virtual object with n_c contact points. For each contact point we use the notation shown in Fig. 1, where $\vec{f_{ci}}$ is the ith contact force vector, $\vec{r_{ci}}$ is the distance vector from the object's center to the ith contact point, and $\vec{a_{ci}}$ is the normal unit vector on the surface of the object. The problem of force distribution on the virtual hand during the execution of a general manipulative task can be formulated as that of finding, for $\vec{f_c}$, an appropriate solution of the following equation:

$$G \cdot \vec{f_c} = \vec{w_e} \tag{1}$$

where

$$G = \begin{pmatrix} I_3, & \cdots & I_3 \\ R_1, & \cdots & R_{nc} \end{pmatrix} \text{ is the } (6 \times 3n_c) \text{ grasp matrix,}$$

I_3 is the 3×3 identity matrix

$$R_i = \begin{pmatrix} 0, & -r_{ciz} & r_{ciy} \\ r_{ciz}, & 0 & -r_{cix} \\ -r_{ciy}, & r_{cix} & 0 \end{pmatrix}$$

$\vec{f_c} = (f_{1x} f_{1y} f_{1z} \cdots f_{ncx} f_{ncy} f_{ncz})^T$: contact forces, and

$\vec{w_e} = \left(-\vec{F_{ext}},\ -\vec{N_{ext}}\right)$: external wrench.

Equation (1) is often accompanied by a number of constraints on the solution $\vec{f_c}$, in order to take into account the unilateral nature of the contacts and the limitations due to static friction (Coulomb law)

$$\frac{\left|\vec{f_{ci}} \cdot \vec{a_{ci}}\right|}{\left|\vec{f_{ci}}\right|} \geq \frac{1}{\sqrt{1+\mu_i^2}} \quad (\mu_i\text{: friction coefficient}) \tag{2}$$

$$\vec{f_{ci}} \cdot \vec{a_{ci}} < 0, \qquad (i = 1, \ldots, n_c) \tag{3}$$

In the general case ($n_c > 2$, no singularities) the system defined by the above relations is indeterminate. The definition of appropriate optimization criteria constitutes undoubtedly one of the major difficulties of the problem. The objective functions proposed in this paper are inspired by relevant studies in the field of force control for multichain robotic mechanisms. However, in the particular context of hand-distributed kinesthetic feedback in VR haptic interaction systems, considered in this paper, these optimization criteria must also reflect sensorimotor control strategies employed by the human operator during various natural grasping and manipulation actions. This point will be also stressed out later on, and some relative research work will be presented giving useful information and ideas to tackle this specific class of problems.

D. Force Distribution for MultiChain Robotic Mechanisms

Since the end of the 1980s, a lot of research work has focused on the development and control of dextrous, more or less anthropomorphic, robot hands [23], [50]. Force control of these mechanisms has raised the problem of force distribution during the grasping and manipulation phases, and that of coordinated action of the motorized elements to ensure global stability of the system. This is often reduced to a linear programming (LP) problem and solved using the Simplex method. Kerr and Roth [24], for instance, have used such a formulation by approximating the friction cones using a set of tangent planes and choosing as objective function the maximization of a safety margin. The problem with such optimization criteria is that they can lead to excessive grasping forces, since no consideration is given for the total effort or the energy supplied by the system. Nakamura *et al.* [37] have proposed a solution to this problem by computing the grasping forces of minimum norm, under static friction constraints. This problem of computing "minimal" internal grasping forces is treated as a nonlinear programming problem, and is solved using the Lagrange multipliers method. Buss *et al.* have proposed to formulate the problem as an optimization on a set of positive definite matrices, under the application of linearized constraints [10]. They introduced a cost index on the basis of a trade-off between the total effort applied on the grasped object and a stability margin.

A similar problem to the optimization of multifingered grasping forces is that of computing the optimal load distribution for the control of multi-legged walking robots and in general for any multi-chain robotic mechanism. The mathematical formulation used is practically identical with the one introduced above, and the proposed methods to solve the load distribution problem are comparable. For instance, Orin and Oh have also proposed the use of the LP method to solve the problem for general locomotion systems [38]. The optimization function was a linear combination of the energy consumption and the static load equilibrium. Cheng and Orin have subsequently proposed a more efficient formulation based on the compact-dual LP method [12]. Kumar and Waldron [28] have also proposed a solution to the problem of optimal load distribution for walking robots, using suboptimal methods based on a novel decomposition in the contact forces space. These methods are numerically superior but are more appropriate for the specific problem of legged locomotion.

E. Non-Linear Programming and Optimization Criteria for the Virtual Manipulation Case

All the above mentioned methods, as well as other similar methods not cited above, aiming to solve the problem of force distribution for robotic mechanisms containing closed kinematic chains, use a mathematical formulation which is similar to the one introduced by relations (1)–(3). To solve the indeterminacy of the system described by these equations, we can follow well known paths and define simple optimization criteria. For instance, by minimizing the following quadratic function:

$$F_1 = (1/2) \sum_{i=1}^{n_c} \left|\vec{f_{ci}}\right|^2 \rightarrow \min \tag{4}$$

we obtain a minimal-norm solution for the contact forces. To take into account the stability margin, a cost index can be introduced computing, for instance, the distance with respect to the friction constraints. However, all these criteria, inspired by studies on robot grasping analysis, do not use any information relative to the "intentional action" of the human hand during virtual grasping. In an interactive virtual prehension system with kinesthetic feedback on the human hand, the *manipulative intention* of the human operator should be monitored on-line and taken into account for the computation of appropriate feedback forces [47].

Let us define what we call "squeezing forces" $\vec{f_{si}}$ as a set of normal contact forces proportional to the intersection between the human hand and the manipulated virtual object at each contact point i ($\vec{f_{si}} = f_{si} \cdot \vec{a}_{ci}$). These forces measure how much the operator is deforming the virtual object locally, and actually encode information concerning the desired manipulative action performed by the human hand. The minimization function F_1 introduced above can be then rewritten in the following form:

$$F_2 = (1/2) \sum_{i=1}^{n_c} \left|\vec{f_{ci}} - f_{si} \cdot \vec{a_{ci}}\right|^2 \rightarrow \min. \tag{5}$$

The system (1), together with constraints (2) and (3), and the function (5) to be minimized, constitute a nonlinear constrained

TABLE I
FINGER/PHALANGEAL CONTRIBUTION FOR A CYLINDRICAL POWER GRIP

Phalanx \ Finger	Index	Middle	Ring	Little
proximal	1.44	1.44	1.08	0.72
middle	0.24	0.24	0.24	0.12
distal	1.92	2.16	1.44	0.96
Total Contribution	3.6	3.84	2.76	1.8

optimization problem. It consists of finding contact forces $\vec{f}_{ci}$ that approach as much as possible the "intentional squeezing forces" $\vec{f}_{si}$ while compensating for the application of the external wrench.

An important point that must be stressed out here concerns the computation of the squeezing forces f_{si}, which in some way determine the amplitude of the feedback forces at each contact point. To compute these quantities at each time instant, it is important to take into account not only information related to the local deformation of the virtual object, but also real data concerning force distribution on the human hand and contribution of each individual finger and phalanx during various types of natural prehensile actions. The computed feedback forces must be, as much as possible, close to the ones naturally experienced by the human hand when manipulating objects in the real world. Such biomechanical data evaluating human natural grasp actions are very difficult to obtain in practice, since they must be based on the use of specialized, ergonomic experimental devices measuring forces on different regions on the human hand. Lee and Rim have developed such a device using pressure sensitive sheets [31]. Their experiments have provided some information concerning force distribution on the human hand, and the percentage contribution of each individual finger and phalanx, when performing cylindrical power grip of variable diameter. More recently, a hand/grasp measurement system has been developed at the National Institute of Bioscience and Human Technology (Tsukuba, Japan) [43]. This device, called *Sensor Glove*, measures forces on 81 points on the palm and surface of the fingers based on the use of electroconductive pressure sensitive sensors. However, a complete set of experimental data, as well as their synthesis into a generalized human grasp taxonomy, still remain limited.

This type of information can be integrated in the computation of the squeezing forces using for instance a simple, linear formula

$$f_{si} = c_i \times K_i \times \delta r_i \tag{6}$$

where δr_i is the local deformation of the virtual object at the $i\text{th}$ contact point, K_i is the simulated contact stiffness and c_i are constants determining the relative contribution of each phalanx and finger at the total grasping force (different for each grasping type). For instance, in the case of a cylindrical power grip these coefficients c_i can be given approximatively the values shown at Table I (see [31] for detailed data on finger/phalangeal percentage contribution).

The computation of the feedback forces $\vec{f}_{ci}$ consists therefore of solving a nonlinear constrained optimization problem, defined by the minimization criterion F_2, (5), and subject to the constraints described by relations (1)–(3). The solution of such a constrained optimization problem can be obtained using various nonlinear programming methods [32] such as for instance the iterative Kuhn–Tucker method. The main drawback of applying such a technique in VR interactive applications is the computation time needed to perform additional iterations, in case one or more of the constraints are not satisfied. Real-time requirements are of major importance for achieving satisfactory realism in such interactive simulation systems. Taking into consideration the particularities of the problem for the application considered in this paper (i.e., haptic interaction within a VE), some simplifications can be made to obtain an analytical solution, as discussed in the following paragraph.

F. Problem Simplification

When manipulating virtual objects, the intentions of the human operator are determined by constantly monitoring the interactions between the virtual hand and the manipulated virtual object. Control of these interactions (for instance if the object must be stably grasped or slip from the hand) is performed by the operator who acts on the haptic interface (in our case, as we will see later, an exoskeleton glove device). Therefore, it seems more appropriate to monitor the stability conditions (2) and (3), instead of imposing them as constraints to the system, and to subsequently determine suitable feedback forces as well as the behavior of the virtual object for each grasping state. The problem of computing optimal feedback forces, in the case of stable virtual grasping [conditions (2) and (3) satisfied] can be solved by minimizing the function F_2 subject only to the constraints defined by the system (1).

To solve this problem in the general case, we can use Lagrange theory and transform it into a system of linear equations which can be for instance numerically solved using the Gaussian elimination algorithm [47]. A more efficient analytical solution to the problem can also be provided by using the pseudo-inverse of the grasp matrix G. A necessary condition for the presence of a minimum for F_2, defined by equation (5), is the following:

$$\nabla_{\vec{f}_c}\left\{\frac{1}{2}\|\vec{f}_c - \vec{f}_s\|^2 - \vec{\lambda}^T(G\vec{f}_c - \vec{w}_e)\right\} = \vec{0} \tag{7}$$

where $\vec{f}_s = [f_{s1}\cdot\vec{a}_1^T, \ldots, f_{sn_c}\cdot\vec{a}_{n_c}^T]^T$ is the $(3n_c \times 1)$ vector containing the squeezing forces and $\vec{\lambda}$ is the (6×1) vector of Lagrange multipliers. This equation can be developed as follows:

$$\vec{f}_c = \vec{f}_s + G^T \cdot \vec{\lambda} \tag{8}$$

or equivalently

$$G\vec{f}_c = G\vec{f}_s + (GG^T)\vec{\lambda} \overset{(1)}{\Longleftrightarrow} (GG^T)\vec{\lambda} = \vec{w}_e - G\vec{f}_s. \tag{9}$$

If the rank of G is equal to 6, which means that the grasping configuration is not singular, we can then write

$$\vec{\lambda} = (GG^T)^{-1} \cdot (\vec{w}_e - G\vec{f}_s). \tag{10}$$

Replacing $\vec{\lambda}$ into (8) we obtain

$$\vec{f}_c = \vec{f}_s + G_R^+ \cdot (\vec{w}_e - G\vec{f}_s). \tag{11}$$

We find therefore an analytical solution for the optimal grasping forces based on the right pseudo-inverse of G: $G_R^+ = G^T \cdot (G \cdot G^T)^{-1}$. This equation can also be written in the following well known form:

$$\vec{f}_c = \left(I_{(3n_c)} - G_R^+ \cdot G\right) \cdot \vec{f}_s + G_R^+ \cdot \vec{w}_e \tag{12}$$

where $(G_R^+ \cdot \vec{w}_e)$ contains the so-called external grasping (or manipulation) forces compensating for the application of the external wrench, and $\{(I_{(3n_c)} - G_R^+ \cdot G)\cdot \vec{f}_s\}$ corresponds to the internal grasping forces. We can here point out that the squeezing forces $\vec{f}_s$, determined by the operator's action on the virtual object, control the intensity of the internal grasping forces and, therefore, the stability of the performed virtual prehensile task.

The solution provided above by equation (11) corresponds in fact to distributing the grasping forces equivalently on all the contact points, which means that the contribution of each force $\vec{f}_{ci}$ at compensating the external wrench $\vec{w}_e$ (term $\{G_R^+\vec{w}_e\}$) is identical and independent of the corresponding squeezing force $\vec{f}_{si}$. This has an important drawback, leading to a weak stability margin for grasping. To tackle this problem, the minimization function F_2, (5), is modified by introducing weight coefficients as follows:

$$F_3 = \frac{1}{2}\sum_{i=1}^{n_c} \frac{\|\vec{f}_{ci} - f_{si}\vec{d}_i\|^2}{|f_{si}|}. \tag{13}$$

This function can be also written as follows:

$$F_3 = \tfrac{1}{2}\left\|S\cdot(\vec{f}_c - \vec{f}_s)\right\|^2 \tag{14}$$

where S is a $(3n_c \times 3n_c)$ diagonal matrix, defined as: $S = \mathrm{diag}[p_{sj}]$, $p_{sj}^2 = (1/f_{si})$, $\forall\, i \in [1, n_c]$, $j \in [3i-2, 3i]$.

Proposition 1: The optimal forces for the minimization of function F_3, defined by equation (13), under the constraints imposed by (1), are given by the following equation:

$$\vec{f}_c = \vec{f}_s + {}^S G_R^{\#}\cdot(\vec{w}_e - G\vec{f}_s) \tag{15}$$

or equivalently

$$\vec{f}_c = \underbrace{{}^S G_R^{\#}\cdot\vec{w}_e}_{(1)} + \underbrace{\left(I_{(3n_c)} - {}^S G_R^{\#}\cdot G\right)\vec{f}_s}_{(2)} \tag{16}$$

where ${}^S G_R^{\#} = S_f^{-1}G^T(GS_f^{-1}G^T)^{-1}$ is a weighted pseudo-inverse of matrix G, with: $S_f = S^TS = \mathrm{diag}[p_{sj}^2]_{j=1,\ldots,3n_c}$

Proof:

$$\nabla_{f_c}\left[F_3 - \vec{\lambda}^T(G\vec{f}_c - \vec{w}_e)\right] = 0$$

$$\iff \nabla_{f_c}\left[\tfrac{1}{2}\left(S(\vec{f}_c - \vec{f}_s)\right)^T\left(S(\vec{f}_c - \vec{f}_s)\right) - \vec{\lambda}^T(G\vec{f}_c - \vec{w}_e)\right] = 0$$

$$\iff S^TS(\vec{f}_c - \vec{f}_s) - G^T\vec{\lambda} = 0$$

$$\overset{|S|\neq 0}{\iff} \vec{f}_c = \vec{f}_s + S_f^{-1}G^T\vec{\lambda}$$

$$\overset{(1)}{\iff} GS_f^{-1}G^T\vec{\lambda} = \vec{w}_e - G\vec{f}_s$$

$$\overset{\mathrm{rank}(G)=6}{\iff} \vec{\lambda} = (GS_f^{-1}G^T)^{-1}(\vec{w}_e - G\vec{f}_s)$$

$$\overset{(17)}{\Longrightarrow} \vec{f}_c = \vec{f}_s + S_f^{-1}G^T\left[(GS_f^{-1}G^T)^{-1}(\vec{w}_e - G\vec{f}_s)\right]. \tag{17}$$

■

The first term of (16) corresponds again to the external grasping forces (also called manipulation forces). This term depends this time on the "squeezing coefficients" p_{si} introduced by the weight matrix S. The contribution of each contact point at compensating the external wrench $\vec{w}_e$ increases with the value of the squeezing forces f_{si}, that is, with the contribution of each contact point at the total grasping force.

TABLE II
EXECUTION TIME FOR THE METHOD BASED ON THE MINIMIZATION OF F_3 AND THE USE OF A WEIGHTED PSEUDO-INVERSE OF THE GRASP MATRIX

n_c	3	5	10	15	20
dt (ms)	2	2	3	5	7

G. Implementation and Numerical Results

1) Computation Time and Complexity: All the methods presented above have been implemented on a HP715 Apollo, 50 Mhz workstation, using C programming language. The first issue was to estimate the numerical complexity of the algorithms by evaluating the evolution of the computation time for different grasping configurations. Various grasping types of increasing complexity have been simulated. The number of virtual hand/object contact points varied from $n_c = 3$ (simple precision grip with three fingers) up to $n_c = 20$ (spherical power grasp).

Table II presents some results demonstrating the performance of the method described by equations (13) and (15) (minimization of F_3) which uses a weighted pseudo-inverse of the grasp matrix G. Computing the pseudo-inverse of G needs the inversion of a 6 × 6 matrix, which is performed using an algorithm based on the Gaussian elimination procedure. It can be noted that

- the complexity of the method is approximately linear with respect to n_c, and
- even in the case of the most complex grasping type (power grip with 20 contact points), the execution time of the algorithm does not exceed 10 ms, which is acceptable for applications that require real-time interactions with a VE.

A task-based sensitivity analysis has also been performed (see [48], [49]), which validated that the force distribution method based on the use of the weighted pseudo-inverse ${}^S G_R^{\#}$, introduced in equation (15), provides superior results with respect to the virtual grasping stability margin, as will be described in Section II-G3.

2) Virtual Prehension: In order to implement the haptic feedback methods described above within a virtual manipulation environment, the system must be capable of monitoring and estimating on-line the contact regions between the virtual hand and the interacting virtual objects. As we have already seen, the computation of feedback forces is based on information such as the local deformation of the manipulated virtual object and the type of the grip performed. In order to obtain all that information on-line, a real-time *collision detection* algorithm has been developed, based on spherical octree structures [46]. This algorithm constitutes the core of the haptic interaction system and enables us to determine the contact configuration between the virtual hand and objects, as well as for the virtual objects between them. The virtual hand consists of two models: a) the graphical model, that is, a polyhedral representation used

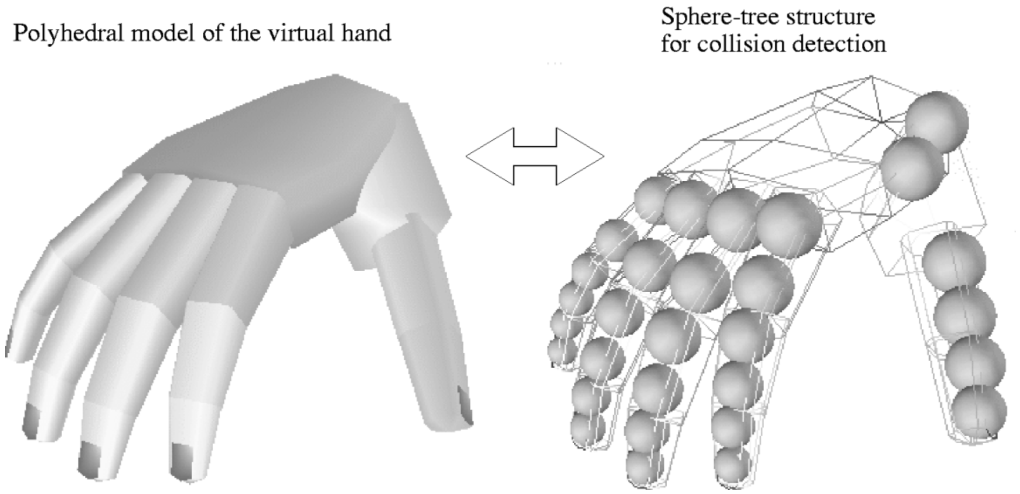


Fig. 2. Virtual models of the human hand.

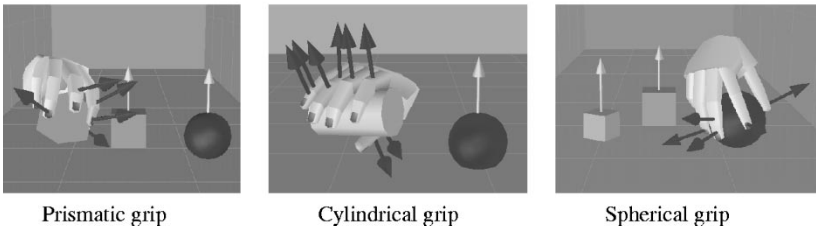

Prismatic grip Cylindrical grip Spherical grip

Fig. 3. Three examples of virtual grasping configurations.

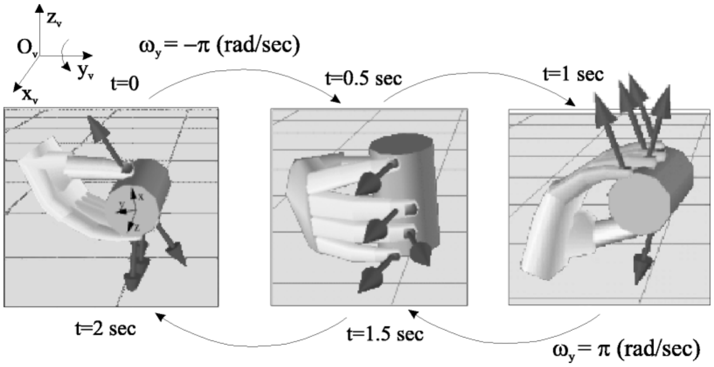


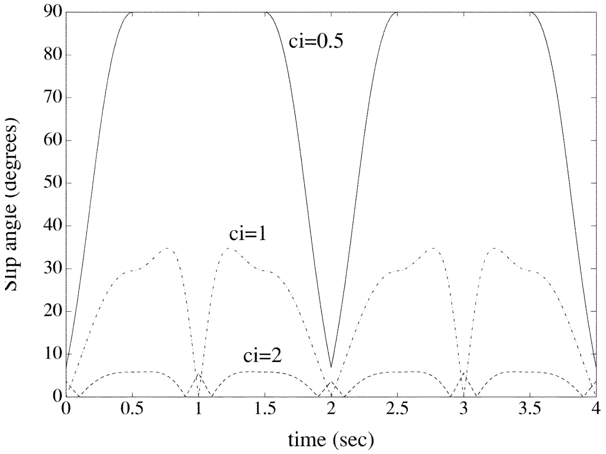
Fig. 4. Manipulation task considered for the sensitivity analysis.

for rendering purposes, and b) the physical model, that consists of a sphere-tree structure, which is used for collision detection purposes (see Fig. 2). This simplified model facilitates considerably the collision detection tasks, enabling the operator to perform a variety of real-time virtual prehensile actions [48]. Fig. 3 shows three examples of such virtual grasping configurations, where the arrows rendered on the virtual hand indicate the normal directions on the detected contact regions.

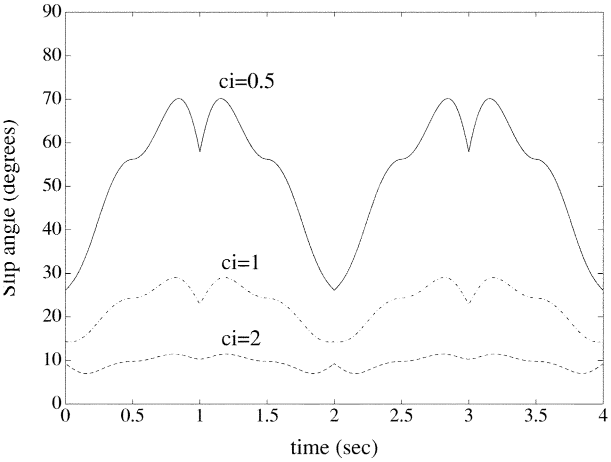
The collision detection and virtual prehension algorithms are of particular importance in the context of a dextrous haptic interaction system, since they form the basis for obtaining on-line all the information necessary for the computation of virtual hand force distribution and the implementation of a whole-hand kinesthetic feedback (including: contact regions between virtual hand and object, normal directions, local deformations and effective stiffness).

3) Sensitivity Analysis: Our goal here is to employ sensitivity analysis techniques to evaluate the behavior and the numerical properties of the methods proposed above, concerning force distribution on the hand during virtual manipulation tasks. The method employed is based on the use of the *"sensitivity matrix"* technique to identify the parameters that seem to have the most significant influence in the overall system's behavior, and to subsequently compute the *"sensitivity trajectories"* deriving from a systematic variation of these parameters around their nominal values. The task considered here consists of a precision grip ($n_c = 5$) for a cylinder with radius $\rho = 5$ cm, and of a reorientation/manipulation of this object in space, as shown in Fig. 4. The weight of the object was taken equal to 10 Nt and its manipulation in space is performed with an angular speed $\omega = \pm\pi$ (rad/s).

An example of sensitivity trajectories is shown in Fig. 5. Two force distribution methods have been compared. Method (A) is based on the use of the pseudo-inverse G_R^+, introduced in equation (11), while method (B) makes use of the weighted pseudo-inverse ${}^S G_R^{\#}$ introduced in equation (15) (Proposition 1). The



(a) Method (A)



(b) Method (B)

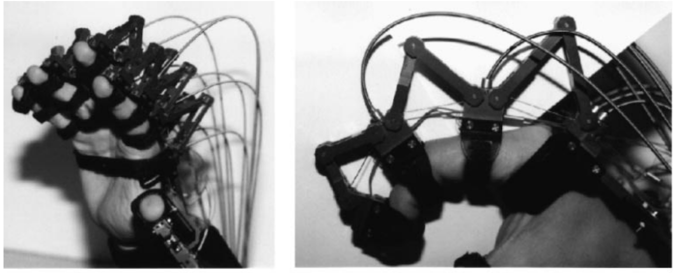
Fig. 5. Sensitivity trajectories for two force distribution methods on the hand. Slip angle for the index, for three different values of its contribution c_i to grasping.

sensitivity graphs obtained (see [48] for details) demonstrated as expected that the grasp stability margin (defined here as: 90°—*Slip_angle*, with $\mathit{Slip\_angle} = \langle -\vec{f}_{ci}, \vec{a}_{ci} \rangle$) using method (B) is always greater than the one given by method (A) (which, for this example, results in an unstable grasping, for instance when 0.5 s $< t <$ 1.5 s, or 2.5 s $< t <$ 3.5 s). In the rest of this paper, method (B) is the one employed for the computation of force distribution on the virtual hand.

III. EXPERIMENTAL EVALUATION: HAPTIC PERCEPTION OF VIRTUAL PHYSICAL CHARACTERISTICS

A. Hardware Configuration

In order to implement and evaluate the whole-hand kinesthetic feedback methodology, proposed in this paper, we used a prototype exoskeleton glove-type device developed at the Laboratoire de Robotique de Paris (the LRP hand master [6], see Fig. 6). The LRP hand master is a device incorporating five fingers with 14 actuated (flexion/extension) and 5 passive (abduction/adduction) DOF. Fourteen dc motors are used for force feedback, which through a cable driven mechanism can apply continuous torque of 0.12 Nt.m resisting flexion on each individual finger joint. Two types of sensors are integrated to the system. Optical encoders are mounted on free pulleys proximal to the axis of each motor, and are used to measure the linear displacement of the cables. Using these measures, the angular flexion of the corresponding finger joints can be deduced, based on a simplified calibration model. Strain gauges are also mounted on the upper part of each phalangeal segment, and are used to measure cable tension forces and, therefore, to compute the joint torque applied on each finger joint. These sensors have good linear characteristics for forces in the range between 0 and 4.5 Nt.



(a) (b)

Fig. 6. Photo of the LRP force-feedback exoskeleton glove: (a) global view, (b) detailed image of the index.

The overall hardware architecture of the experimental testbed, integrating the LRP hand master, is illustrated in Fig. 7. The system consists of the following:

- Two Hewlett-Packard (HP) workstations equipped with graphics accelerator. The first workstation (HP-A) performs graphic rendering of the virtual scene (virtual hand and objects), while the second one (HP-B) assures operations such as collision detection and computations concerning feedback-force distribution on the hand.
- Polhemus Isotrack™ 3–D tracking sensor, providing real-time information on the position and orientation of the human hand in space.
- LRP hand master, which is controlled by a PC (Pentium 133MHz) equipped with a number of AD/DA boards allowing data acquisition for the optical encoders and for the force sensors, as well as data conversion for DC motor control. Communication between the control PC and HP-B is performed via an RS-232 serial communication link, while the two HP workstations communicate using sockets through an Ethernet connection.

B. Haptic Perception and Psychophysics

The rest of the paper focuses on the experimental evaluation of the haptic feedback system described up to now, using methodologies from the field of "psychophysics," the scientific domain studying human perceptual capacities in general. Psychophysical studies focus on the relations between sensations in the psychological domain (subjective factors) and sensations in terms of physical behavior (objective factors). Most of the work in this field is oriented toward estimating absolute and differential thresholds of perception, as well as their variations with respect to other aspects of the sensory stimuli, such as frequency or intensity level. To evaluate the "quality" of the proposed whole-hand kinesthetic feedback modality, we will analyze the performance of the system using objective criteria re-

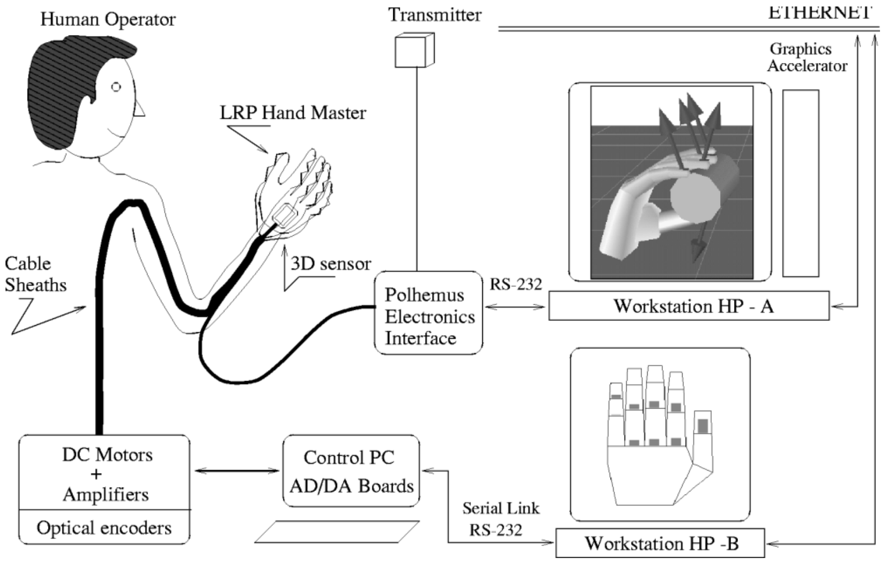


Fig. 7. Hardware architecture of the experimental system.

lated to the human operator's capacity to perceive simulated physical properties of manipulated virtual objects (particularly, virtual weight), through the haptic feedback channel. We will obtain estimates of the differential threshold of haptic perception (also called just noticeable difference or jnd), as well as of the Weber fraction, as a measure of the perceptual capacities of the human haptic system.

Various experimental procedures exist in the literature for the systematic study of human sensory resolution. A general description of such methods can be found in [16]. The two more commonly used experimental procedures to study the detection or the discrimination capacity for different sensory signals are: 1) the *forced-choice* procedure, which is in fact a variation of a more general psychophysical method, called *constant stimuli method*, and 2) the *matching* procedure, which is a variation of the so-called *method of adjustment*. These two methods have often been used to study the capacity of the human sensory system, concerning especially the perception of forces or movements, as well as the perception of physical/mechanical properties of manipulated objects. For instance, Jones [22] has used a so-called contralateral limb-matching procedure to study the perception of forces applied by the flexion muscles of the elbow. The Weber fraction computed by the matching data has been found approximately equal to 0.07, within an interval between 20% and 50% of the maximum voluntary contraction for the elbow joint. A variation of the forced-choice procedure [5] has been used by Durlach *et al.*[14], force [39] and, more recently, compliance [45], viscosity and mass [1]. The experimental results indicate a Weber fraction equal to 0.07 for force, with active finger flexion, and 0.22 for compliance, when eliminating terminal force and energy consumption cues. A similar procedure, based on the general forced-choice method, has also been used by Ross and Brodie [42], and by Raj *et al.* [40], to perform mass and weight appreciation studies. Killbreath and Gandevia [26], have also reported on the manual perception resolution in weight estimation tasks, using different muscles of the human hand.

Summarizing the results obtained by the studies on human haptic perception cited above, the following conclusions can be drawn.

1) All these studies use a variation of the two general psychophysical methods, the forced-choice procedure and the matching procedure. The first one seems more convenient in our case, and has been used for the experimental trials presented in the rest of the paper, especially since concurrent application of controllable forces on both the left and the right hand of the human operator, which would be needed for the implementation of a matching procedure, was not possible.
2) The Weber fractions reported for force and weight perception in the real world, are found approximately equal to 0.10, and seem to increase considerably for small reference forces (around 50 g).
3) Different factors seem to influence the discrimination capacity for manual perception of force. The most important are the intensity of the reference forces, the type of the performed movements (with the best sensitivity obtained when active flexion motion is performed), and the group of acting muscles.

The problem studied in this paper involves, more particularly, the experimental evaluation of haptic sensations created to the human operator when applying whole-hand kinesthetic feedback. The differential thresholds of perception have been estimated in the following three cases:

1) application of a torque localized on an isolated human hand joint, which constitutes the basic functionality of the haptic feedback system;
2) perception of the stiffness of a grasped virtual object, which demonstrates the performance of the system related to the application of internal grasping forces during interactive virtual prehensile tasks (squeezing of a virtual object);
3) perception of the weight of a manipulated virtual object, which is of particular importance, since results of such psychophysical experiments demonstrate the capacity of the

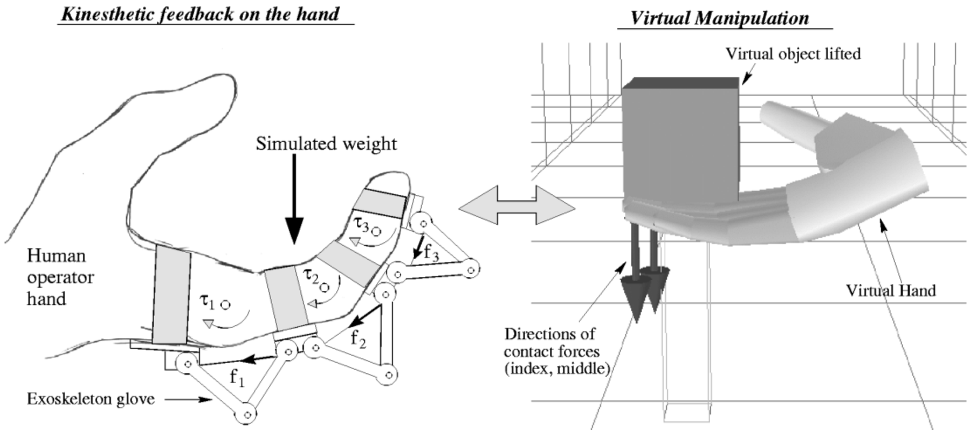


Fig. 8. Manipulation of a virtual object, for the weight perception experiments, and kinesthetic feedback on the hand.

system in rendering external virtual manipulation forces distributed on the human hand.

Experimental results in this last third case are presented and discussed in the following paragraph. An important issue which we try to investigate concerns the relative contribution of the whole sensorimotor capacities of the human hand in perceiving physical properties related to the application of an external wrench, such as weight, during an active virtual manipulation task. Haptic perception of such physical properties is based on multiple sensory signals (afferent signals, coming from a variety of mechanoreceptors, and efferent signals, related to the sense of innervation), which the central nervous system (CNS) has learned to interpret and recognize. This redundancy characterizes, in general, all sensorimotor processes of the human being. The question that can then be raised is how the loss of such redundancy, in the case of haptic interaction within a virtual world, can affect human performance in terms of haptic perception? Are the sensory cues provided by a whole-hand kinesthetic feedback (and limited on the application of torques resisting flexion for some individual finger joints) sufficient for the perception of such physical properties?

C. Virtual Weight Perception

This paragraph presents a set of experimental results evaluating the performance of the proposed whole-hand kinesthetic feedback during an interactive virtual manipulation task. The performance of the system is evaluated by estimating the Weber fraction related to the perception of the weight of a manipulated virtual object. These estimates constitute in fact a measure of the resolution of the haptic feedback system, and indicate the precision with which the human subject can discriminate between different virtual weights. The perception of the weight of a virtual object, within the proposed kinesthetic feedback framework, is of particular interest, since it involves the application not only of internal grasping forces (squeezing forces during active deformation of the manipulated virtual object), but also the distribution of an external static wrench on the human hand.

1) Experimental Procedure: The overall hardware architecture of the experimental testbed has been described in Section III-A. For the experiments described here, each subject was wearing the LRP hand master and interacted with the VE by manipulating a virtual object, as illustrated in Fig. 8. The weight of the virtual object was estimated by performing a series of movements which consisted of consequently lifting the virtual object by a number of active finger flexions. During these movements of the four digits, feedback torques were applied in such a way as to controllably resist flexion on the metacarpophalangeal (MP), proximal and distal inter-phalangeal (PIP and DIP) joints of the index and middle fingers. Other experimental manipulations should be performed in the future to evaluate the performance and the relative contribution of other degrees of freedom of the human hand.

The virtual scene displayed to the subjects consisted of a single object (a virtual cube of 7 cm diameter), placed on a transparent virtual bar of 15 cm length. The position and orientation of the virtual hand was fixed in space, as shown in Fig. 8, in order to ensure the same contact configuration between the fingers and the manipulated virtual object during all experimental trials. The movement of the virtual object has also been constrained on a vertical axis and its amplitude did not exceed 4 cm. These constraints were imposed in order to control the type of manipulation performed by the subjects (flexion/extension movements and vertical displacement of the virtual object) and to eliminate nonsystematic variations on the experimental results caused by other parameters (such as reorientation of the virtual object in space or modification of the directions of the computed virtual forces).

Five subjects (four male and one female) participated voluntarily in the experiments, which were conducted at the Laboratoire de Robotique de Paris. All of them, except one, were right-handed and aged between 24 and 32 years old. The psychophysical method used was a variation of the forced-choice procedure with correct response feedback. This method consists of applying stimuli in pairs (one reference and one comparison stimulus at each trial), and of forcing the subject to choose which one of these two stimuli “feels stronger." The proportion of correct responses (hit ratio) over many trials, with a fixed reference stimulus and varying comparison stimuli, measures the perception (discrimination) capacity for this reference stimulus intensity. A hit ratio of 0.75 was used to obtain the just-noticeable-difference (jnd) and the Weber fraction, correspondingly, for the applied sensory stimuli.

TABLE III
MEAN HIT RATIOS FOR ALL THE VIRTUAL WEIGHT PERCEPTION EXPERIMENTS

Reference weight F_r (*Nt*)	Hit ratio $\delta F(\%) = (F_c - F_r)/F_r$ 5%	10%	20%	30%
1.0	0.50	0.61	0.74	0.79
2.0	0.59	0.67	0.82	0.93
3.0	0.70	0.76	0.86	0.91

The experimental procedure for the virtual weight perception tests was as follows: the subject rested his/her forearm and performed manipulations (active finger flexions) which resulted in lifting the virtual object supported by the hand in the virtual scene. Two weights were applied consecutively during each experimental trial. The subject followed the instructions displayed on the screen of the control PC. After having performed a series of manipulations (3–4 lifting motions) in order to appreciate the first weight (F_1), by pressing any button the weight was automatically modified and the second one (F_2) was applied. The reference weights used for the experiments were $F_r = 1, 2, 3$ Nt, and variations of $\delta F =$ 5%, 10%, 20%, 30% were used for the comparison values. At the end of each trial, the subject answered with a "1," if he judged that F_1 was greater than F_2 for this trial, or else with a "2." Each answer was then added to the set of correct or wrong responses, together with the value of the comparison weight applied during the trial. One experimental series consisted of $2 \times 4 = 8$ trials, where the reference level was held fixed and each comparison weight was applied twice, one time as F_1 and during another trial as F_2. The order of presentation of the comparison values within each experimental series was randomized in order to eliminate anticipation effects. Each complete experimental session, with a fixed reference weight, consisted then of five series of trials, in such a way that at the end of a session all four comparison weights have been applied ten times each, which makes a total of 40 trials for each experimental session.

2) Results: The mean hit ratios, for all the subjects participating in the experiments and for all the experimental sessions, are presented in Table III. The results contained in this matrix are used to compute the jnd for each reference weight, by performing a linear interpolation as illustrated in Fig. 9.

A mean value of hit ratio equal to 0.75 is used to compute the perception thresholds, and corresponds to 75% of correct responses. The values obtained for the jnds are the following:

- Jnd = 0.24 Nt, for $F_r = 1$ Nt;
- Jnd = 0.33 Nt, for $F_r = 2$ Nt;
- Jnd = 0.41 Nt, for $F_r = 3$ Nt.

The Weber fractions (Jnd/F_r), for each reference weight, as well as the corresponding standard deviations (*std*), are the following:

- *Weber-Fraction* = 24.4%, *std* = 5.2%, for $F_r = 1$ Nt;
- *Weber-Fraction* = 16.3%, *std* = 3.5%, for $F_r = 2$ Nt;
- *Weber-Fraction* = 13.5%, *std* = 3.6%, for $F_r = 3$ Nt.

These results are illustrated in Fig. 10.

An analysis of variance (ANOVA) shows a significant difference between the mean Weber fractions for $F_r = 1$ Nt and $F_r = 3$ Nt ($F[1, 8] = 18.1, p < 0.01$). On the contrary, there is no significant difference found between $F_r = 2$ Nt and $F_r = 3$ Nt ($F[1, 8] = 1.7, p > 0.05$). This observation demonstrates a considerable drop of the performance concerning the human capacity to perceive variations between weak virtual forces, and corresponds to the theory that anticipates an increase in the Weber fraction for stimuli of small intensity approaching the absolute threshold of detection. These issues are discussed in the following paragraph.

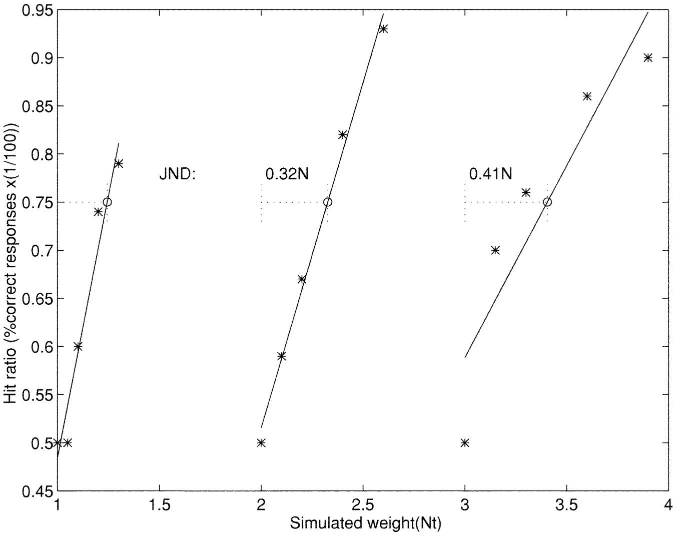


Fig. 9. Computation of jnd for virtual weight perception.

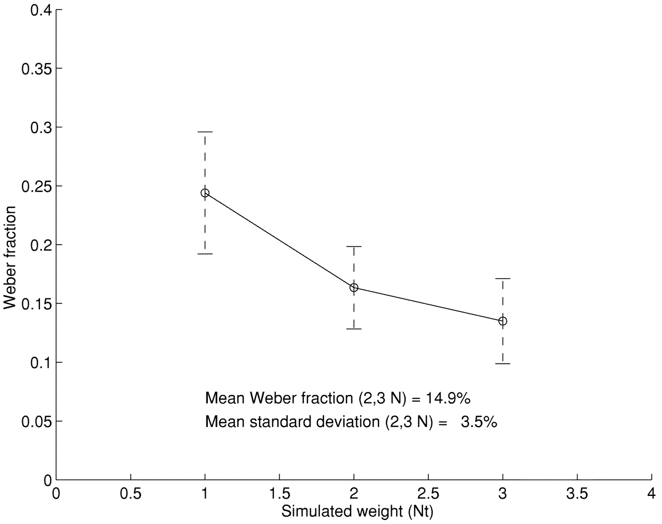


Fig. 10. Weber fraction for virtual weight perception.

3) Discussion: The Weber fractions obtained for virtual reference weights $F_r = 2$ Nt and 3 Nt are similar with a mean value equal to 14.9%. This value is comparable to the ones reported by relevant studies, cited in Section III-B, concerning force/weight perception by the human hand in the real-world manipulation case. For instance, [40] and [42] mentioned Weber fractions of approximately 10%. In the VR-case, presented in this paper, virtual manipulation forces are distributed on the fingers of the human hand and reconstructed in the form of torques applied by the glove mechanism and resisting flexion of the finger joints. This kind of localized kinesthetic feedback is off-course quite limited with respect to the rich sensory signals provided by the human haptic system when manipulating objects and appreciating applied forces in reality. However, the results obtained here for the human haptic perception of a manipulated virtual weight, are quite close to those reported in the literature for real-world manipulation. This leads to a conclusion that the proposed whole-hand kinesthetic feedback seems to be quite efficient, and in any case sufficient for the creation of relatively realistic haptic sensations, particularly for those physical properties related to the application of an external wrench (such as weight) on the virtual manipulation space.

The small increase of the perception thresholds (a mean value of 15% instead of 10% approximately) should be due to the imperfections of the experimental mechatronic system, and especially the stick-slip effect related to the friction of the cables inside the flexible sheaths of the glove device. The presence of a transmission time-delay between the workstation performing dynamic simulation (virtual engine) and the haptic interface control system, can also influence the realism of the simulation and cause a degradation of the real-time interaction sensation for the human operator. A considerable increase in the Weber fraction is also observed for a reference weight $F_r = 1$ Nt. This drop of the performance is significant, as shown by a first-order analysis of variance, and is in accordance with the theory that predicts such a phenomenon when the intensity of the reference stimulus (in signal discrimination) approaches the absolute threshold of perception (in signal detection). However, this threshold here is greater than the one anticipated by other relevant studies, such as in [40] studying force variations between 20 and 200 g and showing an increase for the Weber fraction when the reference force magnitude becomes less than 50 g (while for forces between 100 and 200 g the Weber fraction is found practically constant and approximately equal to 12%). Nevertheless, the results obtained here are globally satisfactory, indicating a mean Weber fraction for virtual weight perception of approximately 15% or less. Conclusively, it can be said that despite the limitations of the system, due mainly to technological constraints, the proposed whole-hand kinesthetic feedback enables the perception of virtual physical characteristics in a consistent and reliable manner.

It should be noted here that the weight discrimination protocol used for the experimental evaluation of the proposed methodology is somehow relatively simple, and does not demonstrate the full power of the theoretical methodology. However, as already stated, weight appreciation is of particular importance in the context of the proposed whole-hand distributed kinesthetic feedback, mainly for two reasons: 1) it involves the application of an external wrench (in this case a "static" force) and its distribution on the finger joints, which calls for the application of a force-distribution method (like the proposed hand-distributed kinesthetic feedback) to convey such an information through haptic feedback localized on the joints (or phalanges) of the human hand, and 2) a large amount of experimental data exists concerning weight/force perception in real-world manipulation, which can be used for comparison purposes to evaluate the proposed methodology. Therefore, although rather simple, the weight perception experiment can be considered as a *"benchmark"* for performance evaluation of a whole-hand kinesthetic feedback, keeping in mind the reasons mentioned above.

Nevertheless, more complex experiments are planned for the future, to more clearly demonstrate in a full extent the power and applicability of the proposed methodology, particularly in the context of a real or simulated *dextrous (multi-finger) telemanipulation task*, involving dynamic aspects of the environment (e.g., physical contact/collisions with stationary or moving obstacles) and distribution of an external wrench (force/moment) on the fingers of the human hand. More specific experiments that are envisaged to evaluate variations of the proposed whole-hand kinesthetic feedback include 1) bilateral teleoperation control of dextrous assembly tasks, and 2) haptic exploration of the external environment (using direct hand actions or via a virtual manipulated probe) involving perception of particular physical properties, useful for instance in general-purpose medical/surgical VR-based simulation and training systems, where human-hand dexterity and skills are critical and must be, as much as possible, preserved.

IV. CONCLUSION

This paper has concentrated on some issues related to human/VR haptic interaction. The general goal of such a system can be defined as integrating the functionality of the human hand (that is, the degrees of mobility, its dexterity and prehensile/manipulative skills, as well as its sensory/perceptual capacities) within a computer simulated environment. We have developed a framework for the synthesis of a whole-hand kinesthetic feedback based on the solution of a generalized force-distribution problem during direct grasping and manipulation of virtual objects. The proposed solution integrates information related to the manipulative "intention" of the human operator, as interpreted by the local deformation ("squeezing") of the manipulated virtual object. It also explicitly includes terms related to external virtual manipulation forces, which can convey additional haptic sensory cues on static or dynamic simulated physical properties in a VE.

The proposed methodology has been experimentally implemented using an exoskeleton force-feedback glove, for the application of controllable feedback torques on individual finger joints of the human hand. A series of test trials has been performed, for the experimental evaluation of the system performance in terms of human haptic perception of virtual weight. The results obtained from the following conducted psychophysical studies demonstrated that:

1) Sensory resolution, as measured by the differential thresholds of perception (Weber fractions), are close to those reported by relevant studies on human haptic perception of real physical characteristics (e.g., weight discrimination for real objects lifted by the human hand).
2) Slight decrease on the performance should be due to the imperfections and limitations of the mechatronic haptic feedback device. This fact shows clearly the constraints related to the limitations of the current technology and the trade-offs that have to be satisfied between various ergonomical and technological factors.

The motivation for the design of a whole-hand sensory feedback system is certainly not to replace existing force-reflecting systems, which can be very efficient in many situations (as is, for instance, the case of direct bilateral teleoperation of robot manipulators). The utility of a whole-hand feedback should be evaluated in the context of specific applications, especially those calling for an increased degree of dexterity and a coordinated control of many degrees of freedom (such as, for instance, when teleoperating a dextrous robot hand). The implementation of such VR techniques can have two different objectives: not only to use the skills of the human operator for the control of increased complexity tasks, but also to study these sensorimotor capacities by simulating a variety of tasks situations and monitoring human performance. In general terms, we can say that an intuitive haptic interaction, integrating a large part of the human hand functionality within a VE, is oriented toward a more natural human-machine interaction, ultimately aiming at a more efficient human skill transfer.

In the future, the proposed kinesthetic feedback will be integrated in the context of a telemanipulation application based on direct human hand actions using VR techniques [25]. Several experimentations will take place including, for instance, co-operation of several robots teleoperated in parallel. Other forms of sensory feedback, such as tactile feedback (vibration or heat) on the palmar surface of the fingers, or force feedback on the wrist, will also be integrated and their relative contribution will be evaluated. The general principle and application of sensory substitution techniques must be further investigated, in order to evaluate which of the available degrees of freedom in a haptic feedback system have a considerable effect on system's performance. This last issue constitutes one of the basic priorities for future work directions, aiming at enhancing and finding optimum compromises for human/computer haptic interaction technology.

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