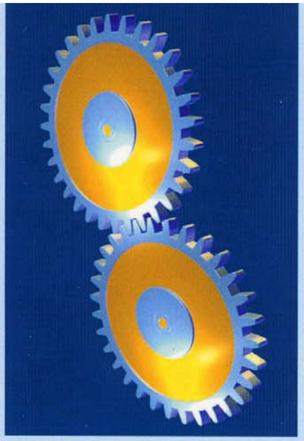
Février 2007



Journal européen des systèmes automatisés

RS série JESA • Volume 41 – n° 2/2007

Robotique et handicap

sous la direction de

Christine Azevedo-Coste

Hermes Lavoisier

Revue des systèmes

RS - séries I2M, JESA, NMT, RIGE

Revue répertoriée dans la base PASCAL de l'INIST-CNRS

ISSN 1269-6935
ISBN 978-2-7462-1815-4
Commission paritaire 63421

Directeur de publication : Patrick Fenouil

Rédaction : Hisham Abou-Kandil
Laboratoire SATIE, ENS de Cachan
61, av. du Président Wilson
94235 Cachan Cedex
Hisham.Abou-Kandil@satie.ens-cachan.fr

Edition : Lavoisier
14, rue de Provigny – F-94236 Cachan cedex
tél. : 33 (0)1 47 40 67 00 fax : 33 (0)1 47 40 67 02
jesa@lavoisier.fr
http://www.revuesonline.com
http://jesa.revuesonline.com

Assessment and training of hand dexterity in virtual environment

Mitja Veber* — Gregorij Kurillo — Tadej Bajd***
Marko Munih*

** University of Ljubljana, Faculty of Electrical Engineering*
Laboratory of Robotics and Biomedical Engineering
Slovenia

{mitja.veber, tadej.bajd, marko.munih}@robo.fe.uni-lj.si

*** University of California at Berkeley*
Department of Electrical Engineering and Computer Science
California, USA

gregorij@eecs.berkeley.edu

ABSTRACT. *We designed two systems for assessment and training of force coordination and hand dexterity in virtual environment. In the first system subjects aligned a real object with the reference virtual object. Pose of hand segments and object was assessed with motion tracking system. The study revealed repeatability of trajectories of movements and a significant delay in the movements of joints when close to their mechanical constraints. The second device was designed to simultaneously assess isometric forces applied by the fingers. Mathematical model of grasping was applied to achieve multi-fingered interaction with virtual objects. Several tasks were developed with the aim to improve grip force coordination and increase muscle strength of patients after stroke through repetitive exercises.*

RÉSUMÉ. *Nous avons conçu deux systèmes pour l'évaluation et l'entraînement de la coordination des efforts et de la dextérité de la main dans un environnement virtuel. Dans le premier système, les sujets devaient aligner un objet réel avec un objet de référence virtuel. La disposition des segments de la main et de l'objet était obtenue à partir d'un système vidéo de capture du mouvement. Notre étude a montré une répétitivité des trajectoires des mouvements et un délai significatif entre les mouvements des articulations lorsqu'elles étaient proches de leurs limites mécaniques. Le second système a été conçu pour permettre d'évaluer simultanément les forces isométriques appliquées par les doigts. Un modèle mathématique de la préhension a été appliqué pour permettre l'interaction des doigts avec un objet virtuel. Plusieurs tâches ont été développées dans le but d'améliorer la coordination des forces de saisie et afin d'augmenter la force musculaire des patients après un accident vasculo-cérébral au travers d'exercices répétitifs.*

KEYWORDS: *grasping, virtual reality, dexterity.*

MOTS-CLÉS : *préhension, réalité virtuelle, dextérité.*

DOI:10.3166/JESA.41.219-238© 2007 Lavoisier, Paris

1. Introduction

The number of injuries of central nervous system (CNS) is increasing each year. The successful recovery of patients with impairments of CNS depends on three key factors: early intervention, task-oriented training, and repetition intensity. It has been shown that repetitive exercises stimulating different sensory modalities, including vision, haptics, proprioception, and audition, can initiate the relearning process inside the CNS (Popović *et al.*, 2002). The training in appropriate environment gives the patients an opportunity to actively participate in the rehabilitation process, which is aimed at regaining the functionality of the affected muscles. Further practice of specific motor skills gives the patients ability to perform simple tasks related to daily activities aimed to improve their quality of living.

Successful integration of virtual reality (VR) into multiple aspects of medicine, psychology and rehabilitation has demonstrated the potential of this technology to build appropriate environments, which allow complete control of the experimental conditions and real-time analysis of data. It has been shown that the training of patients in VR is similar enough to training of motor skills in real environment while increasing their motivation to more actively participate in the rehabilitation process (Holden and Dyar, 2002). In contrast to conventional rehabilitative methods, VR tasks allow full control of the training conditions and requirements, which can be adjusted to performance skills of an individual. Moreover, the high repeatability of tasks and possibility of further off-line analysis of patient's performance provide an opportunity to standardize different diagnostic procedures.

Interaction with objects in virtual environment (VE) through grasping and manipulation is an important feature of the future VR simulations (Boud *et al.*, 1998). The interaction can be pointer activated by a mouse or joystick. More natural interaction with objects using data gloves (Sturman and Zeltzer, 1994) is possible by pushing, pulling or grasping the object by the fingers to change its position, orientation, or geometry. When using visual interfaces the user relies only on visual feedback to obtain information on the state of virtual object. In the real environment the user relies also on proprioceptive and tactile feedback. Providing haptic information on the grasping force and collision with objects increases the sensation of actual presence and improves subject's performance in more difficult tasks.

The most widely used haptic device is PHANToM (SensAble Technologies, Woburn, MA) which allows interaction with virtual objects through one point of contact at the fingertip. Two or three PHANToM devices have been used in parallel to provide multi-fingered interface for manipulation of virtual objects (Hirota *et al.*, 1999; McKnight *et al.,* 2004). For more realistic manipulation, whole-hand haptic devices are used. Whole-hand haptic systems for multi-fingered manipulation must offer high level of mobility of the fingers and haptic feedback in different areas of the hand. Bouzit *et al.* (2002) presented Rutgers Master II system with pneumatic-based actuator platform located at the palm which provides force feedback to four fingers. The system was successfully applied in VR training of stroke patients. A different approach is used with the exoskeleton system CyberGrasp which is worn in combination with the instrumented glove CyberGlove (Immersion Corporation, San Jose, CA). The glove measures joint angles while the exoskeleton provides force feedback to the fingertips. Kawasaki *et al.* (2003) proposed a robotic haptic device where the fingertips of the human operator are attached to a five-fingered robotic hand.

Haptic feedback can be partially replaced by a low-cost alternative such as visual feedback where the haptic information is provided indirectly through visual or other cues (Boud *et al.,* 1998). This approach implements incomplete haptic feedback which is also described as pseudo-haptic feedback (Lecuyer *et al.,* 2000). Compared to VR gloves, where the motion of the fingers is fully unconstrained, pseudo-haptic devices constrain the motion while measuring the force applied to the force sensing elements. The tactile feedback is provided through fingertips when a force is applied to the device. If an increase of the force is required by the VR task, the user will apply higher fingertip force and consequently feel larger resistance due to the motion constraints at the fingertips. Casiez *et al.* (2003) presented a three-degree of freedom haptic device DigiHaptic which allows isotonic and isometric modes of operation.

In this paper we present two original approaches to interaction with VE using an isometric and isotonic input of multiple fingers while preserving haptic information. The method using isotonic interaction with VE is a novel approach to study the manipulation phase of human prehension. In contrast to many studies related to the motor control during the transport and grasp phase of prehension (Jeannerod, 1999; Kuhlen and Kraiss, 2000; Supuk *et al.*, 2005), the study of hand kinematics during the manipulation of a grasped object is not described in the literature related to human grasping. The lack of appropriate methods for the assessment of hand and finger kinematics may be one of the reasons for greater attention being given to other phases of grasping (transport and preshaping). The isotonic method presented in this paper was developed with the aim to quantify the temporal relationship between movements of forearm, hand, and collective finger of unimpaired subjects during the manipulation of a grasped object. We tried to establish whether findings related to an optimal control of transport and grasping phase of prehension could also be applied to the manipulation of an object grasped. In our hypothesis we expected for rough and simple movements at the level of the elbow and wrist joints to precede dexterous movements of the fingers when the hand posture remained invariant.

The second part of our study was focused on the isometric mode of grasping where the fingers have to apply appropriate forces to the object while the movement of the fingertips is constrained. The presented isometric finger device allows the measurement of fingertip forces and torques of the thumb, index and middle fingers. Since the isometric device completely constrains the movement of the fingers, pseudo-haptic approach was used (Lecuyer *et al.*, 2000). Mathematical model of multi-fingered grasping adopted from the analysis of robotic hands (Murray *et al.*, 1994; Montana 1995) was implemented to determine the forces and torques

affecting dynamic response of a virtual object. The forces measured by the finger device were mapped to a virtual object which dynamically corresponds to the resulting force and torque. The finger device was successfully used for multi-fingered grasping in a VE (Kurillo *et al.*, 2005). Several training tasks were programmed with the aim to improve grip force control and grip strength in patients after stroke or other conditions affecting sensory-motor function of upper extremity. This paper, however, is focused on the design of the finger device and realization of the pseudo-haptic control of the VE.

2. Isotonic assessment of hand dexterity

2.1. *System setup*

The experiment setup for assessing motion of hand and object consists of the optical tracking system (Optotrak® Northern Digital Inc.) and ergonomically designed brace firmly attached to a desk as shown in Figure 1a. The brace is designed to prevent elbow flexion-extension while allowing free pronation-supination of the forearm. Although the natural movement of the whole arm is constrained in this way, the wrist and fingers, which predominantly influence dexterity of the hand, are free to move within their range of motion.

Three infra red markers are placed on the brace to acquire the reference frame. Other markers are placed on anatomical landmarks established by palpation. One marker is attached to the elbow, two are placed on the forearm, one is fixed on the wrist, and two markers are attached on the dorsal aspect of hand. Six markers are placed on the prismatic object to ensure that at least three markers are visible in every reachable pose. 3D positions of the markers measured by the camera system are sent *via* local area network to the client computer for processing and visualization.

2.2. *Realization of virtual environment*

A VR library Maverik developed by the Advanced Interfaces Group (Hubbold *et al.*, 2001) was used to build up the VE application. During the experiment the object originating from the real world is displayed within the VE with opaque color (Figure 1a). In the further text this object is referred to as the mobile object. At the same time a semi-transparent reference object with bright colored vertices is shown on the screen. The goal of the task is accomplished when the mobile object is moved inside the reference object. A new reference object pose is shown when deviations of position and rotation are reduced below threshold values of required accuracy. At that time the color of mobile object changes to indicate matching of pose. After two seconds, a new pose of the reference object is displayed which the user has to match.

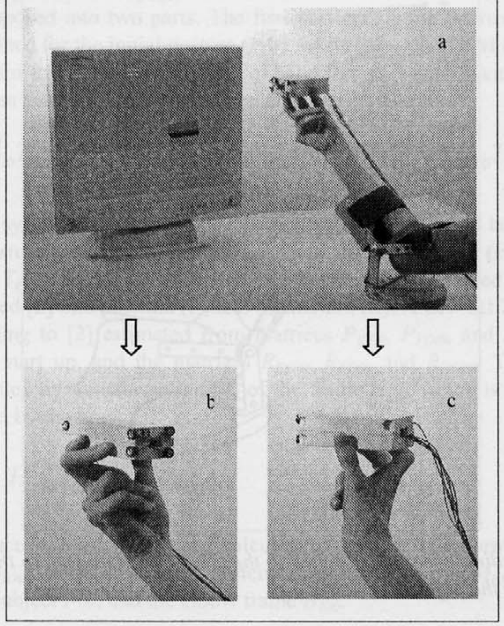


Figure 1. *The right arm is supported by a custom designed brace. The reference position is displayed as a semi-transparent object within the VE. The mobile object is presented with opaque color (a). Screw posture (b), unscrew posture (c)*

During our tests the subjects needed about 15 minutes to get accustomed to the task in the VE. The display of the virtual objects is additionally improved by adding texture gradient and linear perspective. The scale of VE is also equalized with the real world scale. Shallow holes are drilled on the mobile object surface to ensure repeatability of fingertip grasps for different trials and subjects.

Reference poses are chosen based on the poses of objects when used in different daily activities (e.g. fastening a light bulb). The initial pose, which is displayed at the beginning of the trial (Figure 1a), is similar to the real world pose before manipulation. Once the initial pose is reached, the first reference pose, *i.e.* screw, is displayed (Figure 1b - screw). When the mobile object coincides with the reference pose, the subject is instructed to return the virtual object back to the initial pose. A new reference pose (Figure 1c - unscrew) is shown next and the sequence is repeated throughout the trial. The selection of each pose is based on the appropriate position of the forearm, hand and fingers during the manipulation.

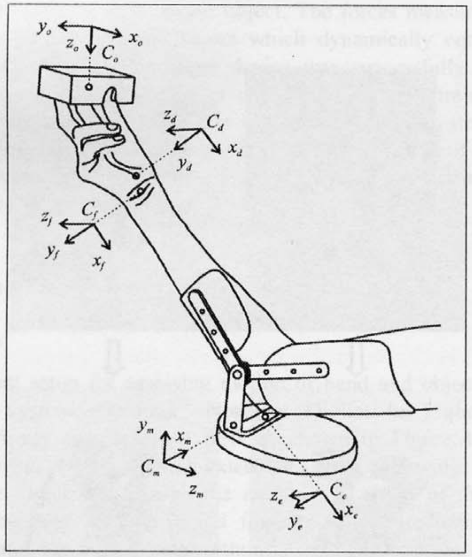


Figure 2. *Coordinate frames attached to the elbow, the forearm, to the dorsal aspect of hand, and to the object*

Poses displayed within the VE are adapted for different sizes of hands as follows. One subject, who does not take part in further studies (i=0), is asked to hold his hand in the initial (j=0; Figure 1a) and several reference postures (j=1, 2; Figure 1b and 1c). Object poses for each posture are recorded and afterwards tested for the same person. Because they are recorded exactly for this subject, their reachability is not questionable. Frames (Figure 2) attached to the elbow (H_{Eij}), the forearm (H_{Fij}), to the dorsal aspect of hand (H_{Dij}), and the object (H_{Oij}) are calculated from 3D positions of markers for the initial and reference postures.

Matrices describing homogenous transformations from elbow to forearm (T_{EFij}; EF), from forearm to hand dorsum (T_{FDij}; FH), and from hand dorsum to object frame (T_{DOij}; HO) are calculated for i=0 and j=0, 1, 2:

$$T_{EFij} = H_{Eij}^{-1} H_{Fij}, \quad T_{FDij} = H_{Fij}^{-1} H_{Dij}, \quad T_{DOij} = H_{Dij}^{-1} H_{Oij} \qquad [1]$$

Matrices related to the initial posture (i=0, j=0), are further decomposed into position (P) and rotation (R) matrices:

$$T_{EFij} = P_{EFij} R_{EFij}, \quad T_{FDij} = P_{FDij} R_{FDij}, \quad T_{DOij} = P_{DOij} R_{DOij} \qquad [2]$$

Matrices T_{EFij}, T_{FDij}, and T_{DOij}, calculated for the reference postures (i=0, j=1, 2), are also decomposed into two parts. The first part equals the matrices, T_{EFi0}, T_{FDi0}, and T_{DOi0}, obtained for the initial posture (j=0), while the second part M_{EFj}, M_{FDj}, and M_{DOj} accounts for translation and rotation of hand frames, which occur with the hand movements from the initial to the reference postures (j=1, 2):

$$M_{EFj} = T_{EFi0}^{-1} T_{EFij}, \quad M_{FDj} = T_{FDi0}^{-1} T_{FDij}, \quad M_{DOj} = T_{DOi0}^{-1} T_{DOij} \qquad [3]$$

During the system start up subject i (i=1,...,n) is instructed to hold his hand in the starting posture (j=0) which is very close to the initial pose (Figure 1a). The matrices T_{EFi0}, T_{FDi0}, and T_{DOi0} for the staring posture are calculated online [1] and then decomposed [2] into position (P) and orientation (R). A new set T_{EFi0}, T_{FDi0}, and T_{DOi0} is according to [2] estimated from matrices P_{EFi0}, P_{FDi0}, and P_{DOi0}, acquired during system start up, and the matrices R_{EF00}, R_{FD00} and R_{DO00}. The initial pose (j=0) is calculated by transformation [4] of the frame H_{Ei0}, which is attached to the elbow and fixed by the brace.

$$H_{Oi0} = H_{Ei0} T_{EFi0} T_{FDi0} T_{DOi0} \qquad [4]$$

The reference poses (j=1, 2) are calculated from the transformation matrices T_{EFi0}, T_{FDi0}, T_{DOi0}, obtained during system start up, matrices M_{EFj}, M_{FDj}, M_{DOj}, calculated for subject i=0, and the elbow frame H_{Ei0}:

$$H_{Oij} = H_{Ei0} T_{EFij} T_{FDij} T_{DOij} \qquad [5]$$

The adaptation of poses presented is based on an assumption that all healthy subjects are capable of similar movements of forearm, dorsum and fingers, as long as joint limits are avoided. If subject i (i=1,...,n) wants to reach pose j, he or she will be able to achieve this by applying the same forearm, dorsum, and finger movements as observed in the subject i=0.

2.3. *Temporal relationship between the movements of hand segments*

The position of the markers during the task performance was recorded for 12 healthy subjects and processed off-line. Figure 2 shows that the activity of the forearm, hand, and fingers can be described separately by transformation matrices which are calculated from frames attached to the arm. 10% of the movement towards the reference pose is carried out after rising time t_R, and 63% after time t_r.

The movements of different subjects were synchronized on the basis of t_R. The time was normalized with the total time required to reach the observed reference pose. The normalization of time was needed to compensate for different speeds

observed among individuals. Roll, pitch and yaw angles (RPY) extracted from the transformation matrices were recalculated into a more compact representation, *i.e.* the quadratic norm (root sum square) of the rotation angles $|RPY|$. The initial values of norms were subtracted and divided by the values acquired at the completion of the task. The normalized norm of the rotational angles represents the portion of the rotation which is necessary to bring the extremity to a reference pose. The normalized values of RPY angles were denoted as normalized rotations r.

The pose of the mobile object relative to the reference object was described by RPY angles and the translation vector XYZ. The initial values of RPY angles and XYZ translations were subtracted in all cases to compensate for the offset values.

3. Results

Repeatability of RPY angles and XYZ translations of the mobile object relative to the reference object was studied in a single subject. In Figure 3 the results are presented as the mean values enveloped by the confidence intervals of one standard deviation.

When a new pose is displayed within the VE, the subject has to first recognize the pose. The recognition phase is followed by the movement from the initial to the reference pose. Standard deviations of position and orientation are reduced during the approaching phase.

Normalized rotations r are presented in Figure 4a and 4b for screw movement and in Figure 4c and 4d for unscrew movement, respectively. Time courses of the normalized rotations r of one subject are plotted in the panels a and c. Vertical dotted lines in the panels a and c denote the time t_r, when forearm reaches 63% of its final rotation recorded in the reference posture. Three normalized rotations r, which belong to the time instance t_r, can be extracted for each subject from matrices describing EF, FH and HO frame transformation. Accordingly, three sets of normalized rotations were obtained. They are presented as box plots in the panels b and d (Figure 4). Dark grey, light grey, and white colors are used to display the contribution of rotation of forearm, wrist, and finger joints, respectively. Horizontal lines of a box plot denote the lower quartile, median, and the upper quartile values. The whiskers indicate the minimum and maximum data values unless outliers are present in which case the whiskers extend to a maximum of 1.5 times the inter-quartile range. A significant difference between medians of two samples is marked by "*".

The wrist and the elbow joints are close to their limitations when performing the screw movement from the initial pose (Figure 4a, b). As a consequence, the object is first rotated by the fingers only, followed by simultaneous rotation of the forearm and hand.

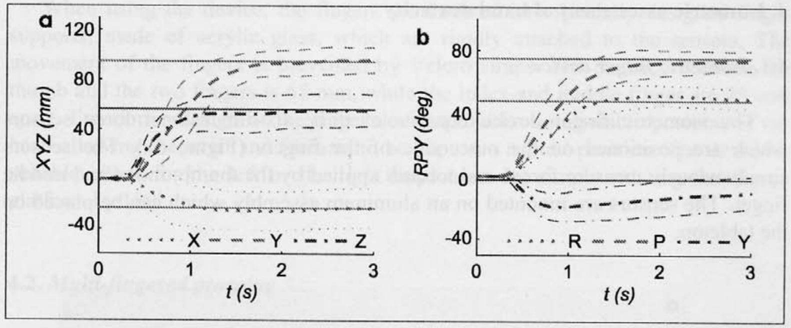


Figure 3. *Repeatability of object trajectories. Object position versus reference object position (a). Object orientation versus reference object orientation expressed with RPY rotational angles (b)*

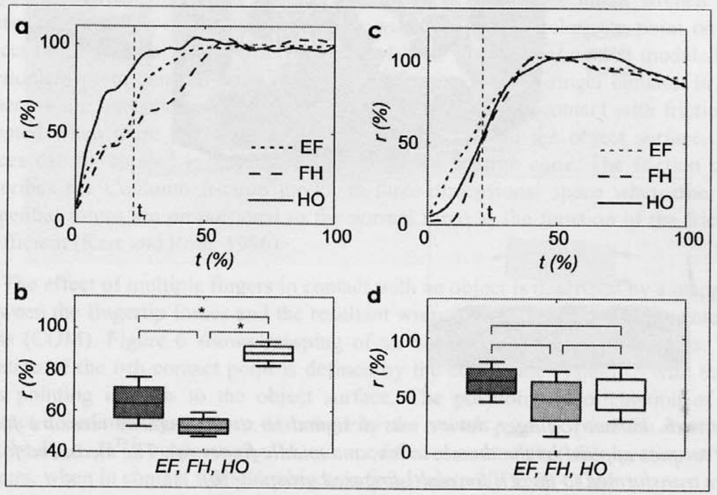


Figure 4. *Time courses of normalized rotations r of single subject for screw (a) and unscrew (c) postures. Normalized rotations for all subjects at time t_r screw (b) and unscrew (d) postures*

During the unscrew movement (Figure 4c) all rotations increased to about the same value after time t_r. The same pattern can also be observed in other subjects (Figure 4d). After time t_r has elapsed, the rotations changed at the same rate.

4. Isometric assessment of hand dexterity

4.1. *Isometric finger device*

The isometric finger device consists of three six-dimensional force sensors which are positioned on the outer side of the fingers (Figure 5a). The sensors simultaneously measure forces and torques applied by the thumb, index and middle finger. The sensors are mounted on an aluminum assembly which can be placed on the tabletop.

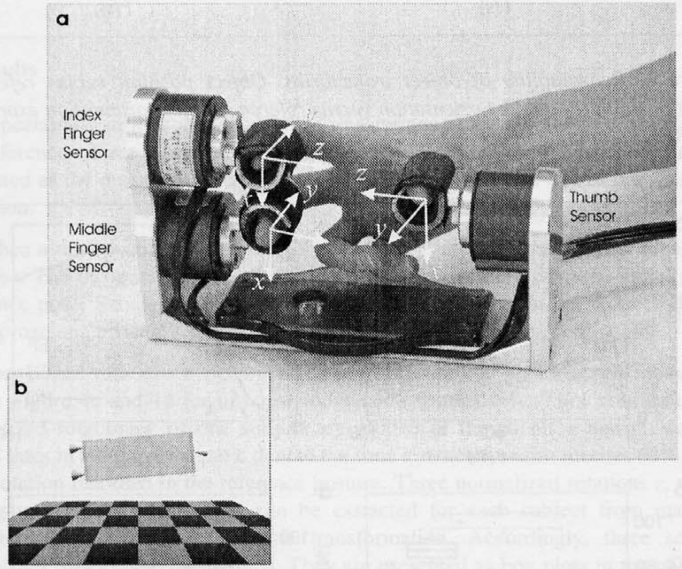


Figure 5. *Isometric finger device was designed to simultaneously measure forces and torques applied by the thumb, index, and middle finger (a). The measured forces were transformed to the VE for multi-fingered grasping (b)*

The measurement range of the sensors is ±150 N for the lateral forces (*Fx* and *Fy*) and ±300 N for the axial force (*Fz*) with the torque range of ±8.0 Nm in all directions. The resolution of the sensors is 0.04 N for the lateral forces, 0.08 N for the axial force and 0.002 Nm for the torques. The data from the three sensors is acquired through a PCI receiver-processor board with the frequency of 100 Hz. The data are filtered in real time by an on-board filter with the cut-off frequency of 32.25 Hz and time delay of approximately 32 ms.

When using the device, the fingers are inserted into specially designed finger supports, made of acrylic glass, which are rigidly attached to the sensors. The movement of the fingers is prevented by Velcro straps. The distance between the thumb and the two fingers is 65 mm, while the index and middle finger are 25 mm apart. Ergonomic design of the finger device provides comfortable position of the hand allowing the wrist and forearm to be kept in a neutral position. The device is suitable either for the left or the right hand users by simply rotating the sensor platform by 180°.

4.2. *Multi-fingered grasping*

In multi-fingered grasping each finger can be described as an independent kinematic chain with multiple degrees of freedom (Murray *et al.*, 1994). At each point of contact additional degrees of freedom exist (*i.e.* contact degrees of freedom), defining the motion between the fingertip and the object. A contact between the finger and the object surface can be described mathematically as a mapping between the forces exerted by the finger and the resultant wrench (*i.e.* vector of three forces and three torques) with regard to a reference point on the object (e.g. center of mass) (Murray *et al.*, 1994). The contact can be modeled as: frictionless point contact, point contact with friction, or soft-finger contact. In this paper we are interested in a point contact with friction. The contact with friction is adopted when there is friction between the fingertip and the object surface. The forces can be applied in any direction within the friction cone. The friction cone describes the Coulomb friction model in three-dimensional space where the two tangential forces are proportional to the normal force as the function of the friction coefficient (Kerr and Roth, 1986).

The effect of multiple fingers in contact with an object is described by a mapping between the fingertip forces and the resultant wrench with regard to object center of mass (COM). Figure 6 shows grasping of an object with multiple fingertips. The location of the *i*-th contact point is defined by the coordinate system C_i with the *z*-axis pointing inwards to the object surface. The position and orientation of the contact coordinate system are described by the vector $\boldsymbol{p}_{oci} \in \mathbf{R}^3$ and the rotational matrix $\boldsymbol{R}_{oci} \in \mathbf{R}^{3\times3}$, respectively. In our model we assume that the location of the fingers, when in contact with the object, is fixed relatively to its COM.

The contact is kinematically described by the wrench basis $\boldsymbol{B}_{Ci} \in \mathbf{R}^{6\times p}$ which defines the number of constraints p. Depending on the contact model, the fingertip can apply forces and torques comprised in the vector $\boldsymbol{f}_{Ci} \in \mathbf{R}^p$. In case of a contact with friction, the contact wrench with respect to the corresponding wrench basis is described as follows:

$$F_{C_i} = B_{C_i} \cdot f_{C_i} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}^T \cdot f_{C_i} \qquad [6]$$

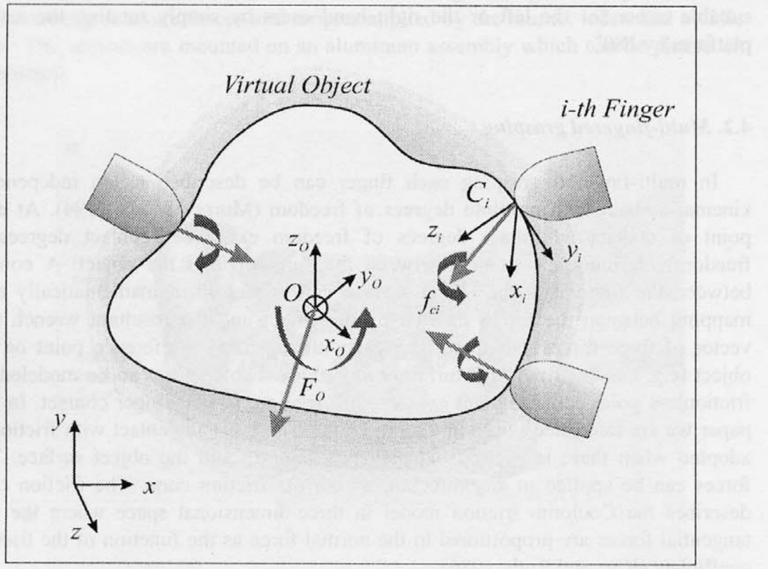


Figure 6. *Forces and torques in multi-fingered grasping of a rigid object*

The components of the force $\boldsymbol{f}_{Ci}$ must lie within the friction cone of the friction coefficient μ defined as:

$$FC_{C_i} = \left\{ f \in \Re^3 : \sqrt{f_x^2 + f_y^2} \leq \mu \cdot f_z, f_z \geq 0 \right\} \qquad [7]$$

To describe the effect of each contact on the object, the contact wrench $\boldsymbol{F}_{Ci}$ is transformed to the object coordinate system using the contact map $\boldsymbol{G}^i \in \mathbf{R}^{6\times p}$:

$$F_{OC_i} = \begin{bmatrix} R_{OC_i} & 0 \\ P_{OC_i} & R_{OC_i} \end{bmatrix} \cdot B_{C_i} \cdot f_{C_i} = G_i \cdot f_{C_i} \qquad [8]$$

The matrix $\boldsymbol{R}_{oci}$ denotes the orientation matrix of the contact coordinate system. The matrix $\boldsymbol{P}_{OCi}$ represents the antisymmetrical matrix of the vector $\boldsymbol{p}_{OCi}$ describing the position of the contact point with regard to the COM.

In case of multiple (k) contacts with the object, the total wrench on the object is defined by a linear transformation of all contact wrenches:

$$F_O = G_1 \cdot f_{C_1} + G_2 \cdot f_{C_2} + \ldots + G_k \cdot f_{C_k} = \begin{bmatrix} G_1 & \cdots & G_k \end{bmatrix} \cdot \begin{bmatrix} f_{C_1} & \cdots & f_{C_k} \end{bmatrix}^T . \qquad [9]$$

Finally, the contact maps $\boldsymbol{G}_i$ of each contact point are collected in the grasp map, defined as the matrix $\boldsymbol{G} \in \mathbf{R}^{6\times kp}$:

$$F_O = G \cdot f_C \qquad f_C \in FC . \qquad [10]$$

The Equation [10] defines the transformation of the matrix of the fingertip forces $f_C \in \mathbf{R}^{kp}$, which lie within the friction cone of the contact model, into the resulting force and torque on the object defined as the wrench vector $\boldsymbol{F}_O \in \mathbf{R}^6$.

For pseudo-haptic grasping with an isometric input device, we fix the relative position of the contact points to the virtual object. Dynamic behavior of the object depends on the resulting wrench at the center of mass. We propose a novel approach for modeling the object dynamics. The virtual object is in its center of mass in all six degrees of freedom (*i.e.* three translations and three rotations) attached to virtual springs with dampers in parallel. By adjusting the stiffness and friction parameters, dynamic behavior of the object is fully controllable, allowing in this way a very high flexibility of the VR environment. With high stiffness of a virtual spring and sufficient friction, the speed of movement in the selected direction can be directly proportional to the input force. With low stiffness of the spring and low friction, the object will behave as if it was suspended on a real spring. The number of degrees of freedom can be limited to restrict the movement in particular directions (e.g. the object is a knob, only rotation is allowed). The proposed dynamic model incorporates object mass, inertia, geometry (e.g. shape, size) and the location of object COM with regard to the global coordinate system.

To describe dynamics of the object shown in Figure 6, we use Newton-Euler equations written in the matrix form:

$$M \cdot \ddot{x} + C \cdot \dot{x} + N \cdot x + g = F_O \qquad [11]$$

In Equation [11] $x \in \mathbf{R}^6$ represents the vector of local coordinates describing the object pose (*i.e.* three position coordinates and three orientation angles), the matrix $\boldsymbol{M} \in \mathbf{R}^{6\times6}$ is the inertia matrix consisting of object mass and inertia parameters, $\boldsymbol{C} \in \mathbf{R}^{6\times6}$ is a diagonal matrix of friction coefficients of the virtual dampers, $\boldsymbol{N} \in \mathbf{R}^{6\times6}$ is a diagonal matrix of stiffness coefficients of virtual springs and $\boldsymbol{g} \in \mathbf{R}^6$ is the gravity vector. In our environment the gravity was excluded from the model because it would be too difficult to compensate using an isometric device. $\boldsymbol{F}_O$ is the total wrench on the object resulting from the fingertip forces and is obtained from the Equation [10].

To obtain the position and orientation of the object in local coordinates, variable x is expressed from the Equation [11] and integrated over time:

$$x = \iint M^{-1}(G \cdot f_C - C \cdot \dot{x} - N \cdot x) \cdot dt^2 . \qquad [12]$$

4.3. *Realization of the VE*

The multi-fingered grasping was implemented using an open source graphics engine MAVERIK (Hubbold *et al.*, 2001). Two C-libraries were programmed to include the mathematical models of the environment and grasping, independent of the visualization engine. For the manipulated object we first defined dynamics parameters (e.g. mass, inertia, compliance of virtual springs, and friction for each degree of freedom). Next, the number of fingers and their position and orientation with respect to the object coordinate system is defined. The pose (*i.e.* position and orientation) of each contact relatively to the object coordinate system is predefined with the object geometry. Three symbolic virtual fingers shown as geometric cones represent the location of each contact at the object surface (Figure 5b). When a threshold force is exceeded, the virtual finger is moved along its axis proportionally to the applied force until the collision with the object surface. The color of the virtual finger is changed from red to green, signaling the activation of contact. The object is grasped when two or three fingers in opposition are in contact with the object. Using the Equation [11], acceleration of the object is determined from all the forces acting on the object (e.g. grip force, frictional force, elastic force of the virtual springs). Next, Euler integration algorithm is applied to acquire new position and orientation of the object. The virtual scene is updated at the end of the rendering loop according to the new calculated values. In each step the fingertip forces and torques, resulting wrench, object position and orientation, velocity and acceleration are stored in a binary file.

5. Results

The results show the outputs as assessed during the performance tests with the isometric finger device. The device was used to manipulate a virtual block inside the developed VE. The subject was instructed to slowly move the object from the initial point to two target points located on the lower left and upper right side of the screen. In both positions the orientation of the object had to be changed for about 90 degrees. The movement of the object was restricted to the vertical plane (aligned with the screen). The object could be only rotated around the normal to the screen plane.

Figure 7 shows fingertip forces as assessed during the performance of the task. The results show an increase of the normal force in all fingers when the object is lifted. The lateral force in the x-direction increased during the transport phase. The middle finger was employed more than the index finger to coordinate the movement of the object. The lateral force applied by the index finger appears to have lower correlation with the thumb force trajectory. The force components in the y-direction of all three fingers were kept below 5 N.

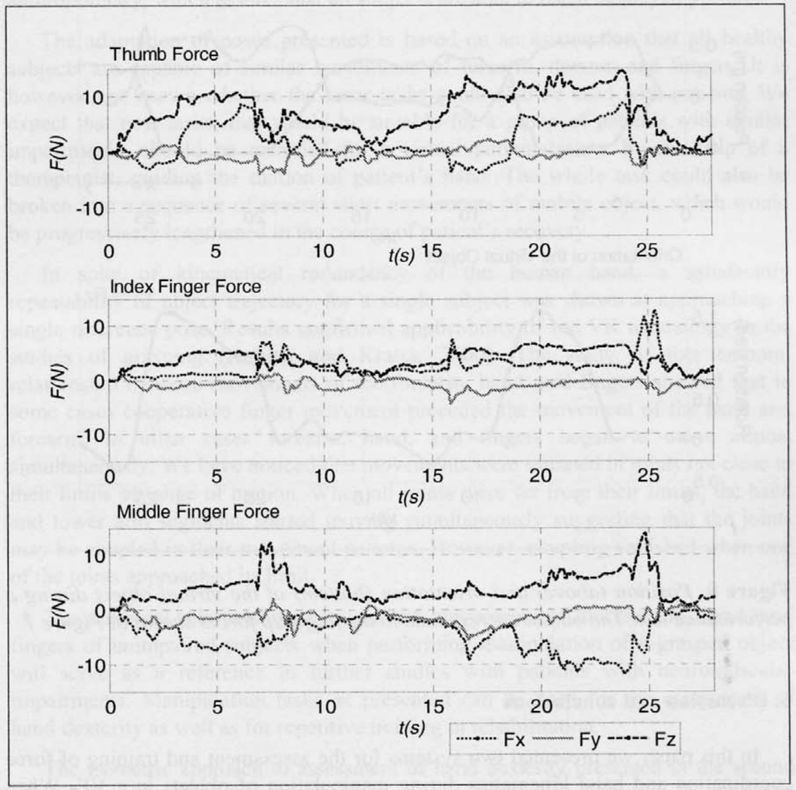


Figure 7. *Fingertip force outputs of a healthy subject during movement of a virtual block across the screen. The subject was asked to transport the object between two marked positions where the object had to be rotated for 90 degrees*

Figure 8 shows the position (above) and rotation (below) of the box during the task performance. The output trajectories are smooth in both directions. In both target points the user was able to rotate the object for about 90˚ ($\pi/2$ rad). During the transport phase, (10-16s) the object was kept stable with only small deviations from the horizontal position.

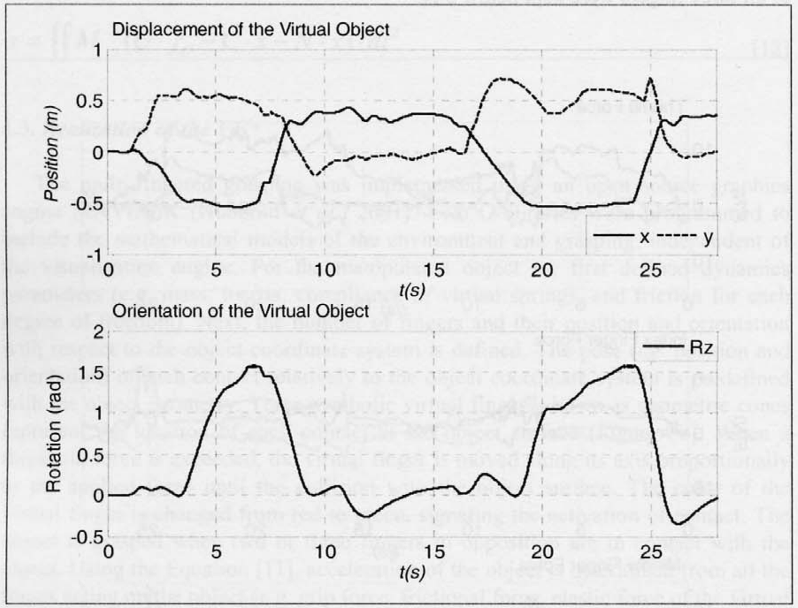


Figure 8. *Position (above) and orientation (bottom) of the virtual object during a performance test. The output corresponds to the fingertip forces shown in Figure 7*

6. Discussion and conclusions

In this paper we presented two systems for the assessment and training of force coordination and hand kinematics during manipulation of objects in a VE. When studying isotonic movements of the hand, the flexion of elbow is prevented by a brace, while the rest of the arm is unconstrained. In the first presented method, the VE is used to provide an augmented visual feedback while manipulating a real object. With this approach the original tactile sensing is preserved, however, no information on the forces applied to the object is acquired. Only relative movements between the hand and lower arm segments were observed in the experiment. The activity of fingers was represented by the relative transformation of the object with respect to the dorsal aspect of hand. A simplified approach is necessary because an appropriate method for online assessment of finger kinematics is not available at the moment. The use of position tracking systems (e.g. optical, magnetic, or acoustic) is limited due to the problems of occlusion and/or relatively large size of markers (Mayer *et al.*, 1992). The exoskeletons and the instrumental gloves on the other hand either impose restrictions on the movement or suffer from rather complex calibration procedures (Todorov and Ghahramani, 2004). Nevertheless, the description of the hand with rigid bodies enables online adaptation to inter-person variability of hand anthropometry, which assures that all subjects are able to reach displayed postures.

The adaptation of poses presented is based on an assumption that all healthy subjects are capable of similar movements of forearm, dorsum and fingers. It is however not known whether the same tasks could also be used with patients. We expect that new tasks, that would be suitable for a group of patients with similar impairments, should be recorded for a virtual patient trainer by the help of a therapeutist, guiding the motion of patient's hand. The whole task could also be broken into a sequence of several short movements of mobile object, which would be progressively lengthened in the course of patient's recovery.

In spite of kinematical redundancy of the human hand, a satisfactory repeatability of object trajectory for a single subject was shown at approaching a single reference pose. Results confirmed applicability of the VR technology in the studies of grasping (Kuhlen and Kraiss, 2000). The study of the temporal relationship between movements of the forearm, hand, and fingers showed that in some cases cooperative finger movement preceded the movement of the hand and forearm. In other cases forearm, hand, and fingers began to move almost simultaneously. We have noticed that movements were initiated in joints not close to their limits of range of motion. When all joints were far from their limits, the hand and lower arm segments started moving simultaneously suggesting that the joints may be coupled in their movement patterns. However, coupling vanished when one of the joints approached its limit.

The temporal relationships between the movements of the forearm, hand, and fingers of unimpaired subjects when performing manipulation of a grasped object will serve as a reference in further studies with patients with neuromuscular impairments. Manipulation tasks as presented can be used for the assessment of hand dexterity as well as for repetitive training in rehabilitation.

The isometric approach to assessment of hand dexterity presented in the second part of this paper was focused on the accuracy of fingertip force coordination. The isometric finger device presented allows accurate measurement of fingertip forces and torques, providing in this way sufficient information to simulate grasping of objects in a virtual world. Although no movement of the fingers is permitted by the isometric device, the visual feedback associated with the object dynamics provides sufficient visual cues to simulate the experience of grasping and manipulation. The results of our

experiments (Kurillo, 2006) showed that healthy subjects and patients after stroke were able to quickly adapt to the isometric control using the fingertip force.

The training of stroke patients could make use of both methods. The isometric approach could be applied in the earliest phase of recovery due to a low functional force required to accomplish the isometric tasks. The VR tasks would be aimed to train fingertip force control in tasks similar to every day living (e.g. rotating a knob, deforming an elastic object, moving an object etc.). Such training could be beneficial to restoration of sensory and motor centers inside the CNS which generate the control signals for finger movement. The patient can use the existing motor skills in the virtual environment to relearn the functional control patterns required for object manipulation. In the later phase of recovery, when sufficient motor and sensory control is gained, the patient could use the isotonic method of training in VR to further enhance his or her abilities. The two presented methods are aimed to complement the existing rehabilitation techniques which are well established in the rehabilitation environment.

The use of both methods enables programming of tracking and step response tasks that require gradual or abrupt change of force or object pose. Root mean square error between the reference and actual force, position and orientation can be used to evaluate the progress of a patient with respect to previous trials. In addition parameters of response dynamics such as rising time and time of completion could be used to assess the success of therapy. Finally, the segmentation of the whole movement into the movements of forearm, wrist, and fingers, could help in prescribing exercises to further improve coordination in hand movements.

The main drawback of the instrumented gloves and haptic hand devices used as input to the VR tasks is in difficult donning and doffing when training patients with spasticity. In addition to safety factors, the performance can also be influenced by fatigue when using exoskeleton and other robotic devices attached to a patient's hand. Isometric devices have no moving parts, making the device much safer to use with patients. The cost of isometric devices is mainly determined by the price of the force sensing system.

The isometric finger device could be redesigned to include more cost-efficient force sensors with fewer degrees of freedom. The results have shown that two degrees of freedom per finger would be sufficient for realization of the existing VR training tasks. The input device could be further adapted to specific tasks in rehabilitation therapy. Similar device could be used as an input interface for multi-fingered interaction in VE. The device could consist of a joystick-type handle with force sensors for the fingers. Two or three fingers would be inserted into specially designed finger fixations while the hand would control the position of the handle. The isometric mode would be applied for multi-fingered grasping while the isotonic mode would be used to control the position of the virtual hand.

Acknowledgement

The finger device was designed within the ALLADIN project, funded by the European Commission under the 6th Framework Programme, IST Programme, Priority 2.3.1.11 – eHealth, IST Contract No.: IST-2002-507424 and also supported by the Slovenian Research Agency.

7. References

Boud A.C., Baber C., Steiner S.J., "Object manipulation in virtual environments: effects of visual and haptic feedback", *Proceedings of ICAT '98*, Tokyo, Japan, 1998, p. 124-128.

Bouzit M., Burdea G., Popescu G., Boian R., "The Rutgers Master II-new design force-feedback glove", *IEEE/ASME Trans. Mechatronics*, vol. 7, 2002, p. 256-263.

Casiez G., Plénacoste P., Chaillou C., Semail B., "The DigiHaptic, a new three degrees of freedom multi-finger haptic device", *Proceedings of Virtual Reality International Conference*, Laval, France, 2003, p. 35-39.

Doeringer J.A., Hogan N., "Serial processing in human movement production," *Neural Netw.*, vol. 11, 1998, p. 1345-1356.

Hirota K., Hirayama M., Tanaka A., Kaneko T., "Representation of force in object manipulation", *Proceedings of ICAT'99*, Tokyo, Japan, 1999.

Holden M.K., Dyar T., "Virtual environment training: A new tool for neurorehabilitation," *Neurology report*, vol. 26, 2002, p. 62-71.

Hubbold R., Cook J., Keats M., Gibson S., Howard T., Murta A., West A., Pettifer S., "GNU/MAVERIK: A microkernel for large-scale virtual environments", *Presence*, vol. 10, 2001, p. 22-34.

Jeannerod M., "Visuomotor channels: Their integration in goal-directed prehension," *Human Movement Science*, vol. 18, 1999, p. 201-218.

Kawasaki H., Takai J., Tanaka Y., "Control of multi-fingered haptic interface opposite to human hand", *Proceedings of 2003 IEEE Int Conf. on Intelligent Robots and Systems*, Las Vegas, NV, 2003, p. 2707-2712.

Kerr J., Roth B., "Analysis of multifingered hands", *Int. J. Robot. Res.*, vol. 4, 1986, p. 3-17.

Kuhlen T., Kraiss K.F., "How VR-based reach-to-grasp experiments can help to understand movement organization within the human brain," *Presence*, vol. 9, 2000, p. 350-358.

Kurillo G., Measurement and evaluation of grasping in virtual reality, PhD Dissertation, University of Ljubljana, Ljubljana 2006. (http://robo.fe.uni-lj.si/pdf_avi/Kurillo_doktorat.pdf)

Kurillo G., Mihelj M., Munih M., Bajd T., "Grasping and manipulation in virtual environment using 3By6 Finger Device", *Proceedings of ICORR*, Chicago, IL, 2005.

Lécuyer A., Coquillart S., Kheddar A., Richard P., Coiffet P., "Pseudo-haptic feedback: can isometric input devices simulate force feedback?", *Proceedings of IEEE Inter. Conf. on Virtual Reality*, New Brunswick, NJ, 2000, p. 83-90.

Mayer K., Applewhite H.L., Biocca F.A., "A survey of position trackers", *Presence: Teleoperators and Virtual Environments*, vol. 1, 1992, p. 173-200.

McKnight S., Melder N., Barrow A.L., Harwin W.S., Wann J.P., "Psychophysical size discrimination using multi-fingered haptic interfaces", *Proceedings of EuroHaptics 2004 Conference*, Munich, Germany, 2004.

Montana D.J., "The kinematics of multi-fingered manipulation", *IEEE Trans. Robot. Autom.*, vol. 11, 1995, p. 491-503.

Murray R.M., Li Z., Sastry S.S., *A mathematical introduction to robotic manipulation*, CRC Press, New York, NY, 1994.

Popović D.B., Popović M.B., Sinkjær T., "Neurorehabilitation of upper extremities in humans with sensory-motor impairment," *Neuromodulation*, vol. 5, 2002, p. 54-67.

Sturman D.J., Zeltzer D., "A survey of glove based inmput," *IEEE Computer Graphics & Applications*, vol. 14, 1994, p. 30-39.

Supuk T., Kodek T., Bajd T., "Estimation of hand preshaping during human grasping," *Medical Engineering & Physics*, vol. 27, 2005, p. 790-797.

Todorov E., Ghahramani Z., "Analysis of the synergies underlying complex hand manipulation," *Proceedings of the 26th Annual International Conference of the IEEE EMBS*, San Francisco, California, USA 2004.