Two Finger Grasping Simulation with Cutaneous and Kinesthetic Force Feedback

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Abstract. This paper presents an experiment of two finger grasping. The task considered is the peg-in-hole and the simulated force feedback is cutaneous or kinesthetic. The kinesthetic feedback is provided by a commercial haptic device while the cutaneous one is provided by a new haptic display proposed in this work, which allows to render at the fingertip a wide range of contact forces. The device consists of a mobile surface, which interacts with the fingertip, actuated by three wires directly connected to the motors placed on the grounded structure of the display. This work summarizes the design of the proposed display and presents the main relationships which describe its kinematics and dynamics. Results showed that cutaneous feedback exhibits improved performances when compared to visual feedback only.

1 Introduction

Cutaneous feedback is important to simulate interactions with objects in a virtual environment. Single-contact haptic devices, such as the Omega devices (Force Dimension, CH), provide haptic feedback, consisting of both cutaneous and kinesthetic forces, to the user, making him/her aware of the relative position of neighboring parts of the body by means of sensory organs in muscles and joints [1].

Watanabe *et al.*, in [2], developed a system for controlling cutaneous sensations of surface roughness by applying ultrasonic vibration to the surface. In [3] the authors proposed an approach to provide human cutaneous sensation using surface acoustic wave. A pulse-modulated driving voltage excited temporal distribution of shear force on the surface acoustic wave substrate. The force-friction distribution was perceived as cutaneous sensations at receptors in the skin.

A widely-used approach for providing cutaneous sensations is employing dynamic pin-matrices. Ikei *et al.*, in [4], developed a cutaneous display which has 50 vibrating pins. The vibratory pin array included 5x10 contact piano-wires 0.5mm in diameter, aligned in a 2mm pitch with a vibration frequency of 250Hz. In [5] the authors developed a pin-array cutaneous display, composed of a 6x5 pin-array actuated by 30 piezoelectric bimorphs. It was able to display planar distributed and Braille cell patterns. Pin-arrays were also employed in [6], where the authors used a solenoid, a permanent

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magnet and an elastic spring to develop a miniature pin-array cutaneous module. The elastic springs in the actuators were separated into several layers to minimize the contactor's gap. In [7] the authors used electrostatic force and friction control to render surface roughness sensations. The display consisted of stator electrodes and a thin film slider, on which an aluminium conductive layer was deposited.

Minamizawa *et al.*, in [8,9], presented a wearable and ungrounded haptic display able to simulate weight sensations of virtual objects. The device consisted of two motors and a belt able to deform the fingertip. When motors span in opposite directions the belt applied a perpendicular force to the user's fingertip while, if motors span in the same direction, the belt applied a tangential force on the skin. That device was used in [10] to provide cutaneous feedback in an industrial application involving heavy duty machines, and in [11] for experiences of remote cutaneous interaction. A similar device has been also used in [12], where the authors presented a new approach to sensory substitution in haptics called *sensory subtraction*. They substituted haptic feedback, consisting of both cutaneous and kinesthetic forces, with cutaneous feedback only, in order to achieve the stability of the system and outperform other conventional sensory substitution techinques. More recently, Bau *et al.* developed in [13] a technology to provide cutaneous sensation while moving fingers on touch screens. The touch panel presented has a conductive layer coated with an insulating layer, which the finger rests upon. When voltage difference was applied between the finger and the conductive layer, a normal attractive force was induced. By alternating the voltage, it was possible to modulate the friction force felt by the moving finger. A similar device has been presented in [14], where the authors developed a system, named VerroTouch, for providing cutaneous feedback to surgeons during telerobotic surgery. VerroTouch measured the vibrations caused by tool contact and recreates them on the master handles for the surgeon.

This paper presents a three DoF cutaneous display used to interact with objects in a virtual environment. The device is able to apply contact forces to the fingertip by applying forces to the vertices of a rigid platform by means of three wires. Three servomotors are in charge of moving the platform and applying the requested force to the user's fingertips, ensuring precision, strength, and lightness.

The system provides cutaneous stimuli only and most of the kinesthetic feedback is missing. The proposed device is similar to the wearable haptic device presented in [15] but there are relevant differences which are worth underlining. The cutaneous display here presented can be easily integrated with other systems which provide kinesthetic stimuli (see Sec. 4), it uses three servo motors and can render higher forces at the fingertip. The idea of providing realistic cutaneous sensations while using haptic interfaces has been also discussed in [16]. However, the thimble there presented was only able to provide the cutaneous sensation of making and breaking contact with virtual surfaces.

An important contribution of the paper is to show how this cutaneous device can be used to simulate a pinch grasp and perform a peg-in-hole task.

The paper is organized as follows: the cutaneous device is presented in Sec. 2. In Sec. 3 the statics analysis of the device, represented as a three DoFs parallel mechanism is summarized. An experiment, carried out to evaluate the user experience while using the device in a virtual environment, are presented and discussed in Sec. 4. Finally Sec. 5 addresses concluding remarks and perspectives of the work.

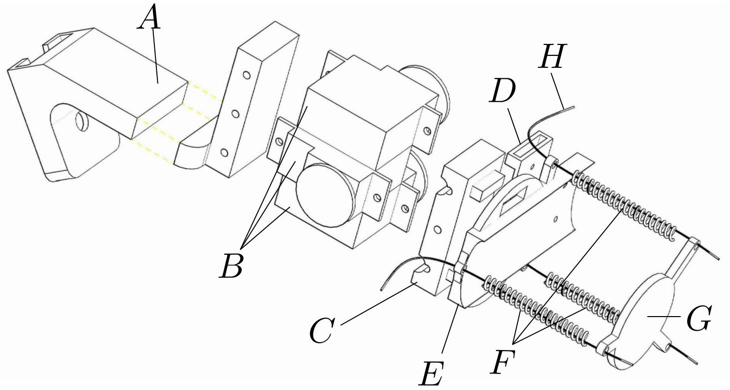


Fig. 1. A sketch of the three DoFs cutaneous device. Three servo-motors control the lengths of three wires in order to tilt the mobile platform according to the virtual surface being touched.

2 Device Description

Fig. 1 sketches the main idea of the proposed three DoFs cutaneous device while a prototype is shown in Fig. 2. It consists of a static part (parts A,C-E in Fig. 1), and a mobile part (part G), able to apply the requested stimuli to the fingertip's volar surface.

Referring to Fig. 1, the user should place the fingertip between part G and part E (see also Fig. 2). Three springs, placed between the mobile platform and the static part, keep the platform horizontally aligned with the rest of the device. Three servo-motors (B) control the length of the three wires (H) connecting the mobile platform vertices to the static platform (E), making the platform able to apply the requested force at the user's fingertip. The mobile platform model is described and discussed in Sec. 3. The actuators used for the device prototype are three HS-55 MicroLite Servo motors [17]. The motors are fixed to part C and D of the device structure. Part A is devoted to connect the cutaneous display to an external support.

In this work the device will be fixed to the end-effector of an Omega 3 haptic device in order to provide kinesthetic feedback, if necessary, and/or track the position of the finger. The mechanical supports for the actuators and the mobile platform are made using a special type of acrylonitrile butadiene styrene, called ABS*Plus*™ (Stratasys Inc., USA). The device uses a velcro strap, fixed to part D, to be fasten tightly to the fingers and make it easier to wear (see Fig. 2). The total weight of the whole device, including actuators, springs, wires, and the mechanical support is about 45g.

The force applied by the device to the user's finger pad is balanced by a force supported by the structure of the device on the back of the finger (part E). This structure has a larger contact surface with respect to the mobile platform (part G) so that the local pressure is much lower and the contact is mainly perceived on the finger pad and not on the back side of the finger. This idea was inspired by the *gravity grabber* presented in [8,9] and previously summarized, where a wearable haptic display was employed to simulate weight sensations of virtual objects. Both devices are able to render cutaneous stimuli and most of the kinesthetic feedback is missed.

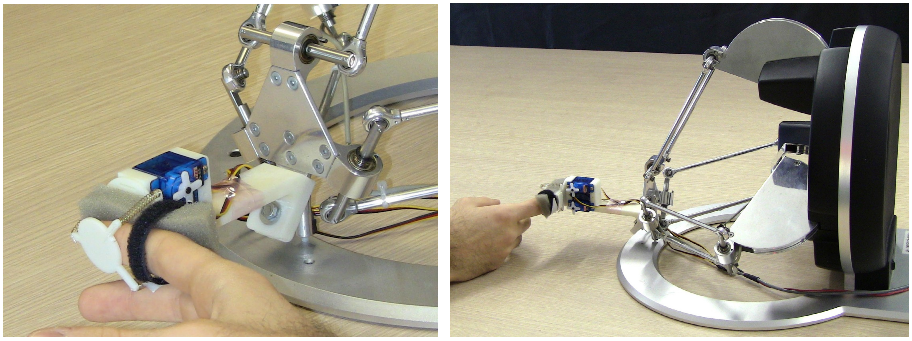


Fig. 2. The three DoFs cutaneous display prototype: the three servo-motors move the platform according to the virtual surface being touched. The device is fixed to the end-effector of the Omega 3 haptic device.

3 Device Model

The kinematic structure of the proposed device is similar to the wearable display described in [15]. The main differences is that the one proposed in this paper is not designed to be portable. The power of the acuators is larger and three passive springs have been included in the design. Similarly to the device proposed in [15], the cutaneous platform can be modeled as a three DoFs parallel mechanism, where the static part is fixed and the mobile platform is in contact with the finger pulp.

The mobile platform is moved acting on three wires connecting its vertices to the actuators. Three springs, which contain the wires, make possibile to fix the platform in a reference configuration. The model of the device presented in this paper differs from the one described in [15] because:

- in this case the wires do not follow the finger shape but a straight line from the static to the mobile platform,
- in the evaluation of actuator forces the compliance of the three springs is taken into account.

Let $w_p = [f_p^{\mathrm{T}} \;\; m_p^{\mathrm{T}}]^{\mathrm{T}} \in \Re^6$ be the wrench applied to the mobile platform (expressed with respect to S_0), and $Q = [Q_1 \;\; Q_2 \;\; Q_3]^{\mathrm{T}}$ the vector of force (norms) applied to the wires, being their directions defined by the unitary vectors s_1, s_2, and s_3 respectively. We can express the external wrench as a function of the force applied to the wires

$$w_p = J_p^{\mathrm{T}} Q. \tag{1}$$

where $J_p \in \Re^{3\times 6}$ is the Jacobian matrix and can be evaluated from the analysis of the differential kinematics of the platform. The wire forces Q_i are given by the sum of two components

$$Q_i = Q_{a,i} + Q_{p,i}$$

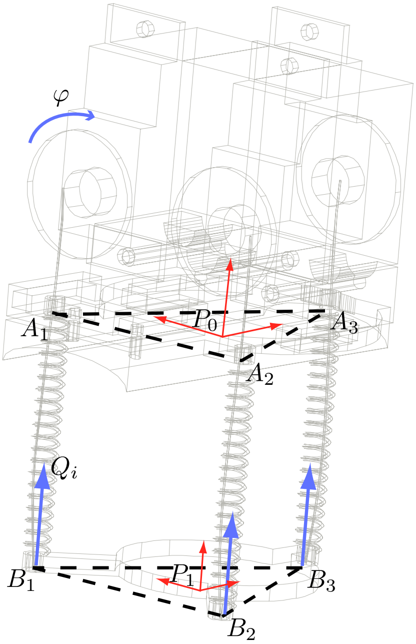


Fig. 3. The three DoFs haptic display kinematic scheme

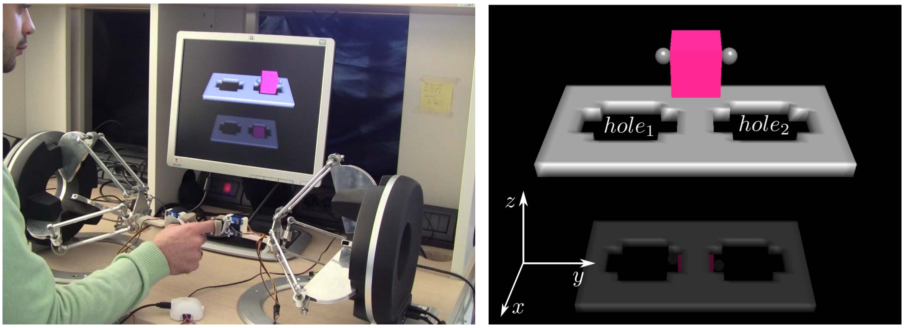
where $Q_{a,i}$ is the force applied by the i-th actuator, proportional to the motor torque, i.e. $Q_{a,i} = T_i r_i$, T_i is the i-th motor torque and r_i is the i-th motor pulley radius. $Q_{p,i}$ is the contribution generated by the spring deformation

$$Q_{p,i} = k_i \left(\|d_i\| - \|d_{i,o}\| \right)$$

where k_i is the spring stiffness, $\|d_i\|$ is the actual wire length, $\|d_{i,0}\|$ is the nominal spring length.

The described device is underactuated, since it has only three actuators to control the six-dimensional displacement of the mobile platform, so it is not possible to find a one-to-one relationship between the wire lengths and the platform displacement and orientation in the three-dimensional space. If the platform touches the fingertip, the platform displacement $\xi = [p_x \quad p_y \quad p_z \quad \alpha \quad \beta \quad \gamma]^{\mathrm{T}}$ produces a deformation of the fingertip that leads to a contact stress distribution. In quasi static condition the stress distribution on the fingertip is balanced by the wrench applied by the platform w_p [18].

Different mathematical and numerical models of the fingertip have been proposed in the literature. In [19], for example, a 2D continuum fingertip model is described, in which the finger is approximated by an homogeneous, isotropic and incompressible elastic material. Serina *et. al*, in [18], developed a model that incorporates both inhomogeneity and geometry of the fingertip is proposed. In [20] an experimental method for obtaining the 2-dimensional skin tension/extension-ratio characteristics of living human skin is described. In [21] the authors conducted an experiment in order to characterize the response of the *in vivo* fingertip pulp under repeated and compressive loadings,



(a) Experimental setup (b) Virtual environment

Fig. 4. Experimental setup and virtual environment. The user had to wear two cutaneous devices, one on the index and one on the thumb finger, and then grasp the virtual cube and complete the peg-in-hole task as fast as possible.

aiming to better understand the force modulation by the pulp. The force/deformation behavior of the fingertips in the lateral, or shearing, direction, is studied in [22]. Actually, the stress/strain behavior of the fingertip under shearing forces is non linear, in fact in [23] the authors experimentally quantified the anisotropic and hysteretic behaviour of the fingertip deformation under the application of tangential forces.

In this paper we consider a linear relationship between the resultant wrench and the platform displacement. In other terms we assume that the platform configuration ξ is proportional to the wrench w_p

$$\xi = K^{-1} w_p \tag{2}$$

where $K \in \Re^{6\times6}$ is the fingertip stiffness matrix. In this preliminary study an isotropic elastic behaviour is assumed for all the components of the stiffness matrix: $K = kI$, $k = 2$N/mm [24].

From the control point of view, the device can be represented as a non linear, multi-input multi-output (MIMO) coupled system. Different control strategies can be considered, we can control for instance the force applied by the platform to the fingertip or the position and orientation of the mobile platform.

In particular, in the device position control, the motors are regulated so that the mobile platform reaches a reference configuration. The inverse kinematics of the parallel mechanism allows to evaluate the corresponding reference cable lengths. These values are compared to the actual ones and then the error drives the PD controllers of the motors.

4 Experiment

The cutaneous device here presented can tilt the mobile platform according to the reaction force of the virtual object being touched, enhancing users' illusion of telepresence.

This experiment aimed at evaluating user dexterity while using the device here presented in a virtual environment. The cutaneous device was fixed to the end-effector of an Omega 3 haptic device, as shown in Fig. 2. Users were able to interact with virtual objects in a virtual environment built using CHAI 3D [25], an open-source set of C++ libraries for computer haptics and interactive real-time simulation. The experimental setup is shown in Fig. 4.

Nine participants, six males, three females, age range 19–35, took part to the experiment, all of whom were right-handed. Five of them had previous experience with haptic interfaces. None of the participants reported any deficiencies in their perception abilities. The subjects were asked to wear two cutaneous devices, one on the thumb and one on the index finger (see Fig. 4) and complete a peg-in-hole task in a virtual environment [26,27]. The virtual environment was composed by a cube and two holes (named $hole_1$ and $hole_2$, as shown in Fig. 4b). The two holes were 3.5cm deep (x-direction), 3.5cm wide (y-direction), and 0.5cm high (z-direction). The peg was a cube with an edge length of 3cm. Therefore the hole had a tolerance of 0.5cm in the x and y directions.

The task consisted in grasping the cube from the ground, inserting it into the right hole ($hole_2$), then in the left hole ($hole_1$) and then again in $hole_2$ and $hole_1$, therefore the correct sequence was $hole_2$, $hole_1$, $hole_2$, $hole_1$. The task started when the user grasped the object and finished when the user inserted, for the second time, the peg in $hole_1$. At least half of the length of the peg had to be inserted in the hole in order to move to the next hole and the peg had to be inserted from the top to the bottom. When the object was correctly inserted into a hole, the color of the peg changed[1].

Each participant made twelve repetitions of the peg-in-hole task, with three randomized trials for each force feedback modality proposed:

- both kinesthetic and cutaneous feedback provided by the Omega 3 haptic devices and the proposed cutaneous devices (task $K + C$),
- kinesthetic feedback only provided by the Omega 3 haptic devices (task K),
- cutaneous feedback only provided by the cutaneous devices (task C),
- no force feedback (task N).

Visual feedback, as shown in Fig. 4, was always provided to the users. To evaluate the performance of the different force feedback modalities, the time needed to complete the task was recorded, together with the forces generated by the contact between the two proxies, controlled by the user, and the cube. A spring $k_o = 600$N/m is used to model the contact force between the proxies and the object. Data resulting from different trials of the same task, performed by the same subject, were averaged before comparison with other tasks' data.

Fig. 5a shows the average time elapsed between the instant the user grasps the object and the instant it completes the peg-in-hole task. The collected data of each task passed the D'Agostino-Pearson omnibus K2 normality test. Comparison of the means among the feedback modalities was tested using one-way ANOVA (no repeated measures). The means differed significantly among the feedback modalities. Post-hoc analyses (Bonfferroni's multiple comparison test) revealed statistically significant difference between all the groups, showing that the time needed to accomplish the task depends on the feedback modality employed in the experiment.

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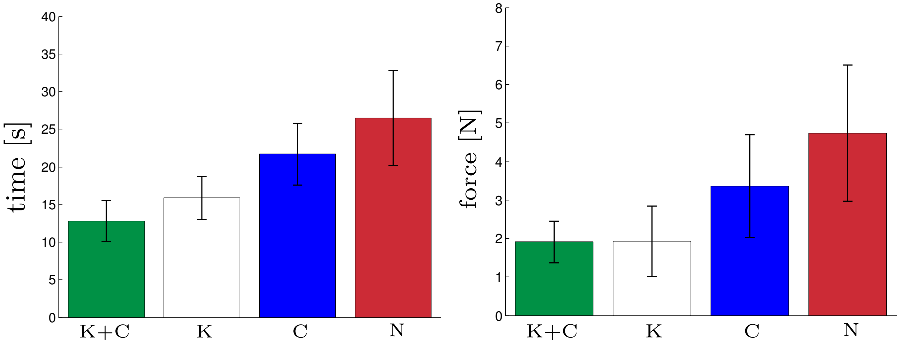
[1] A short video of the experiment can be found at http://goo.gl/O3Ax8



(a) Completion time (b) Contact forces

Fig. 5. Time to completion of the peg-in-hole task and force generated by the contact between the two proxies and the object during tests with both kinesthetic and cutaneous feedback (task $K+C$), kinesthetic only (task K), cutaneous only (task C), and no force feedback at all (task N)

The subjects, while receiving both kinesthetic and cutaneous feedback (task $K+C$), completed the task in less time when compared to that obtained while receiving kinesthetic feedback only (task K), and using cutaneous feedback only (task C) yields to significant better results than employing no force feedback at all (task N). This means that employing cutaneous feedback improves subjects' performances in terms of time needed to complete the task proposed. Using kinesthetic feedback (both in task $K+C$ and K) produced better performances, as expected, with respect to employing cutaneous feedback only or no force feedback at all.

Fig. 5b shows the average forces generated by the contact between the two proxies, controlled by the user, and the cube along the y-direction, i.e. the one perpendicular to the object surface (see Fig. 4b). Note that a higher force fed back to the user means a larger penetration into the virtual object and a higher energy expenditure during the grasp. Measuring the average of intensities of the two contact forces is a widely-used approach to evaluate energy expenditure during the grasp [28]. The collected data of each task passed the D'Agostino-Pearson omnibus K2 normality test and a one-way ANOVA test was performed to evaluate the statistical significance of the differences between tasks. The post-hoc analyses (Bonfferroni's multiple comparison test) revealed no statistical significance between the two tasks employing kinesthetic feedback (task $K+C$ and K) while it revealed a difference between the task employing no force feedback (task N) and the one using cutaneous feedback only (task C). It is worth noting that cutaneous feedback yielded to a minor force fed back to the operator and to a minor penetration into the virtual object in comparison to the no-force modality.

5 Conclusion and Future Works

In this work an experiment of pinch grasp with cutaneous feedback only has been presented along with a new device used to exert cutaneous forces at the two finger pads.

A peg-in-hole experiment has been carried out. Nine users had to complete the peg-in-hole task employing four different force feedback modalities: no force feedback at all, kinesthetic feedback, cutaneous feedback, and both kinesthetic and cutaneous feedback. Results showed that employing cutaneous and kinesthetic feedback lead to a higher quality of the grasp (i.e., a smaller energy expenditure) and it improves the performances in terms of time needed to complete the given task with respect to the kinesthetic only feedback.

Future developments will include the analysis of other types of control schemes and the employment of three force sensors placed at the vertices of the mobile platform. The sensors will provide a measurement of the force the platform is applying to the user's fingertip and will allow to modulate correctly the force applied by the cutaneous device.

New experiments of interaction with virtual objects in virtual environments and in augmented reality scenarios will be performed in the next future. Finally, work is in progress to validate the device with more subjects.

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