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# Teleoperation System with Haptic Feedback for Physical Interaction with Remote Environment

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**Abstract:** The paper focuses on the teleoperation system TeleTA with haptic feedback designed to realize haptic communication with remote human, to achieve high level of maneuverability of robot arm in unstructured environment, and to increase effectiveness of physical Human-Robot interaction. The human operator directs the robot arm to the target position, while manipulator sensory system provides safe physical interaction with environment. In order to achieve awareness of collision, to support operator with valuable information (stiffness and shape of contacting object), and to realize robot-mediated haptic communication, we developed the innovative tactile and haptic displays, namely, BraTact (for presenting the cutaneous information) and FlexTorque (for presenting the kinaethetic feedback).

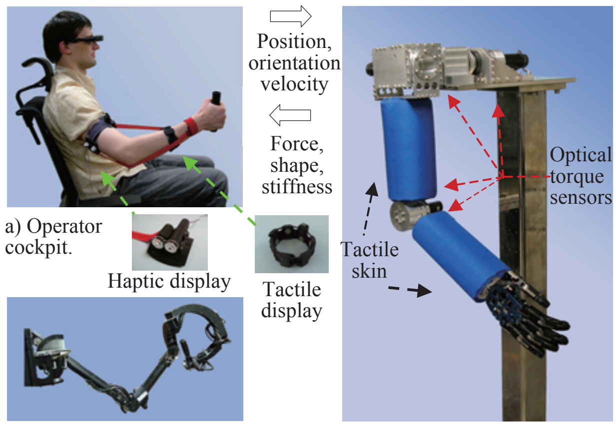
**Keywords:** Teleoperation, haptic display, tactile display.

## 1. INTRODUCTION

Humans can perform dexterous manipulations in remote place by means of teleoperation. The teleoperation is also intended for realization complex cooperation tasks with human beings (physical collaborative interaction) and haptic communication. Remote robot must ensure stable contacting with object in case of collision and safe physical interaction. The additional important information about objects (shape, stiffness, location, fixation, etc.) can be gathered while contacting. The presentation of obtained knowledge about environment to a human operator in real time can considerably improve the performance of teleoperation. The delivering force feedback in the case of collision and during physical interaction is absolutely necessary. However, typical teleoperation system provides force feedback only to human hand [1]. Moreover, sensory system of slave robot does not provide safe interaction along entire structure. Additionally, master arm integrates motors of high power. In the case of malfunction it can harm operator.

The paper focuses on the teleoperation system **TeleTA** (**Tele**operetion system with wearable **T**actile and haptic display on the operator arm surface providing **A**wareness about contact state, contacting object properties, and interactive forces between slave robot and environment) designed by us to achieve high level of maneuverability of robot arm and to perform cooperative tasks with humans in a safe manner. Distributed optical joint torque sensors and local admittance controllers endow our robot arm with the distinctive capability of safe interaction with surroundings along entire manipulator surface (including joints). The applied force vector is calculated from the values of joint torques and contact point coordinates [2].

Master side (Fig. 1(a)) includes exoskeleton robot arm with 6 DOF (Fig. 1(b)), tactile display BraTact to present cutaneous stimulation when collision with object is detected, and haptic display FlexTorque to present forces during physical collaborative tasks and




b) Master arm. c) Remote robot iSoRA.

Fig. 1 Robot teleoperation system TeleTA.

haptic communication. The orientation of the human elbow is controlled by the tilt sensor.

Developed teleoperated robot iSoRA has 4-DOF: Roll, Pitch, Yaw joints of a shoulder, and Pitch joint of an elbow. Each joint is equipped with optical torque sensor directly connected to the output shaft of harmonic drive and magnetic encoders.

Proposed sensory system of slave robot (tactile skin to detect contact point and torque sensors distributed into each joint for measurement of applied force) patterns on the human tactile system. Our sense of touch can be separated into kinesthetic and coetaneous. Kinesthetic stimulations, produced by forces exerted on body, are sensed by mechanoreceptors in the joints, tendons, and muscles enabling us to estimate forces being applied to body [3]. On the contrary, mechanoreceptors in the skin layers are responsible for cutaneous stimulation sensation enabling stimuli localization.

The robot arm is covered with Kinotex tactile sensor [4]. In order to recognize the contact region, we employed the watershed algorithm. However, applied force sensitivity of Kinotex is very low due to high non-linearity of the output, and limited sensing range. The task of load measurement is accomplished by the



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developed optical torque sensors enabling the torque measurement with high accuracy [5]. The spring members attached to the first, second, and third/fourth joints were designed to measure torque of ± 12.5 Nm, ± 10.5 Nm, ± 4.5 Nm, and have resolution of 10.77 mNm, 9.02 mNm, and 4.31 mNm, respectively.

In order to realize realistic haptic interaction (holding, pushing and contacting the object) with environment and haptic communication with human beings (e.g. handshaking), the force feedback is required. The aim of our research is to develop wearable tactile and haptic display to present realistic feedback (cutaneous and kinesthetic stimulus) to the operator's arm.

In the remainder of the paper we describe the development of wearable device FlexTorque aimed at force feedback, and ergonomic tactile display BraTact for presentation of contact location and physical properties of contacting object.

## 2. DESIGN OF HAPTIC DISPLAY FlexTorque

Most of the force feedback master devices are similar in sizes to slave robot and are equipped with powerful actuators. Such systems pose dangerousness for human operator and in case of failure during bilateral control can harm human. In the last years there have been several attempts to make the force feedback devices more compact, safe, and wearable.

In [6], an exoskeleton-type master device was designed based on the kinematic analysis of human arm. Pneumatic actuators generate torque feedback. The authors succeeded in making the lightweight and compact force reflecting master arm. However, the force-reflection capability of this device is not enough to present contact forces effectively. Moreover, pneumatic actuators have large time delay, complicated control, and limited workspace.

An artificial pneumatic muscle-type actuator was proposed [7]. Wearable robotic arm with 7 DOF and high joint torques was developed. Robotic arm uses parallel mechanisms at the shoulder part and at wrist part similarly to the muscular structure of human upper limb. It should be noted, however, that dynamic characteristics of such pneumatic actuator possess strong nonlinearity and load-dependency, and, thus, a number of problems need to be resolved for its successful application. The large weight of 4 kg and cumbersome structure significantly degrade the initial concept of human-friendly and wearable design.

In order to achieve human-friendly and wearable design of haptic display, we analyzed the amount of torque to be presented to the operator arm. Generally, there are three cases when torque feedback is needed. The first case takes place when haptic communication with remote human needs to be realized. For example, the person handshakes the slave robot and joint torques are presented to the operator. Such interaction results in very small torque magnitude (in the range of 0-1.5 Nm). The second situation takes place when slave robot transports heavy object. Here, the torque values are much higher than in previous case and torque magnitude depends on the load weight. However, continuous presentation of high torques to the operator will result in human muscle fatigue. We argue that downscaled torque indicating direction of the force would be informative enough. The third and the worst case of contact state in term of interactive force magnitude is collision. It is obvious that high force will be produced when robot collides with moving object. However, the result of collision with fixed object (as it is often the case) is immediate discontinuation of the operator's arm motion. Therefore, the power of torque display must be enough to only fixate the operator arm. For the case of collision with movable obstacle, the haptic display should induce human's arm motion in the direction of the impact force, decreasing thus the possible damages.

The idea behind novel torque display FlexTorque is to reproduce human muscle structure, that allows us to perform dexterous manipulation and safe interaction with environment in daily life. Main functions of the muscles are contraction for locomotion and skeletal movement. A muscle generally attaches to the skeleton at both ends. Origin is the muscle attachment point to the more stationary bone. The other muscle attachment point to the bone that moves as the muscle contracts is Insertion. Muscle is connected to the periosteum through tendon (connective tissue in the shape of strap or band). The muscle with tendon in series acts like a rope pulling on a lever when pulling tendons to move the skeleton (Fig. 2).

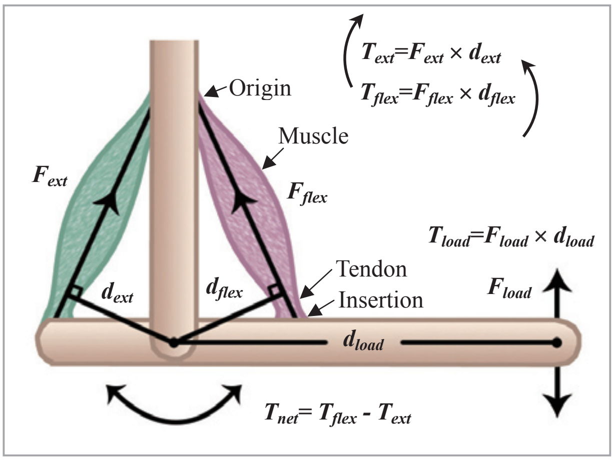


Fig. 2 Structure and action of a skeletal muscle.

When we hold a heavy object in a palm, its weight produces torques in the wrist, elbow, and shoulder joint. Each muscle generates a torque at a joint that is the product of its contractile force and its moment arm at that joint to balance gravity force, as well as inertial forces, and contact forces. Thus, we can feel object weight.

Because muscles pull but cannot push, hinge joints (e.g. elbow) require at least two muscles pulling in opposite direction (antagonistic muscles) [3]. The torque produced by each muscle at a joint is the product of contractile force (*F*) and moment arm at that joint (*d*). The net torque $T_{net}$ is the sum of the torques produces by each antagonistic muscle. Movement of human limbs is produced by coordinated work of muscles acting on skeletal joints. The structure of the developed torque display FlexTorque is presented in Fig. 3.

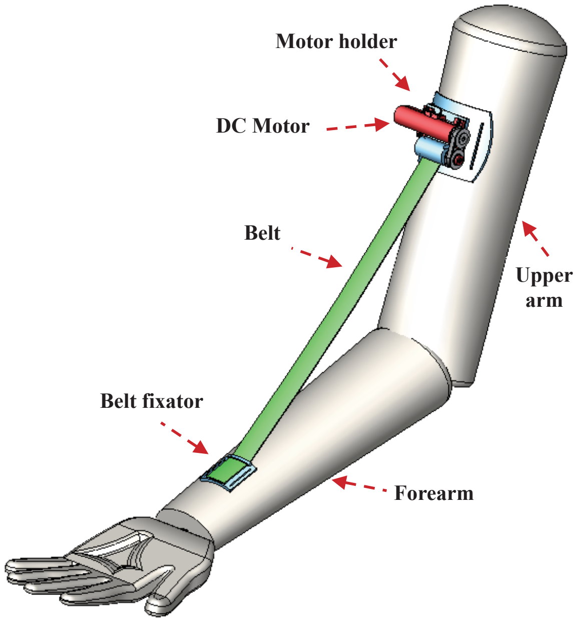


Fig. 3 FlexTorque on the human's arm surface.

FlexTorque is made up of two DC motors (muscles) fixedly mounted into plastic Motor holder unit, Belts (tendons), and two Belt fixators. The operation principle of the haptic interface is as follows. When DC motor is activated, it pulls the belt and produces force $F_{flex}$ generating the flexor torque $T_{flex}$. The oppositely placed DC motor generates the extensor torque $T_{ext}$. Therefore, the couple of antagonistic actuators produce a net torque at operator elbow joint $T_{net}$. We defined the position of the Insertion point to be near to the wrist joint in order to develop large torque at the elbow joint.

The position of the operator's arm, when flexor torque is generated, is shown in Fig. 4 (where $\theta$ stands for angle of forearm rotation in relation to upper arm).

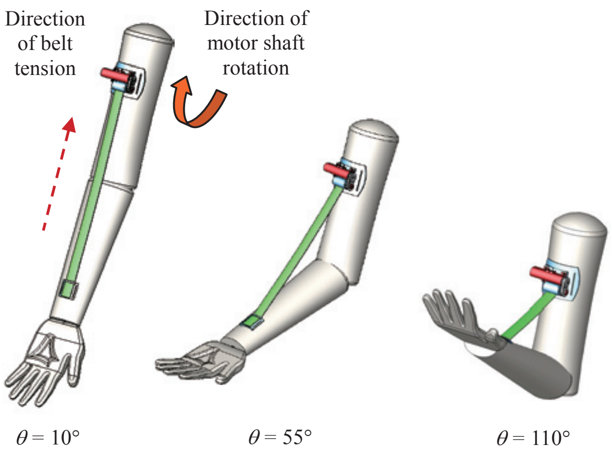


Fig. 4 Positions of the human's arm under flexor torque.

Let us consider the calculation procedure of the net torque value. The layout of the forces and torques applied to the forearm during flexion is given in Fig. 5.

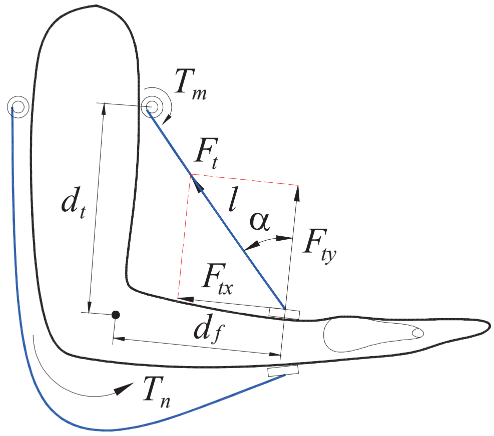


Fig. 5 Diagram of applied forces and torques.

The tension force $F_t$ of the belt can be derived from:

$$F_t = \frac{T_m i}{r}, \tag{1}$$

where $T_m$ is the motor torque, $i$ is the gear ratio, and $r$ is the shaft radius.

The net torque $T_n$ acting at the elbow joint is:

$$T_n = F_{ty} d_f = F_t d_f \cos(\alpha), \tag{2}$$

where $d_f$ is the moment arm.

The angle $\alpha$ varies according to the relative position of the forearm and upper arm. It can be found using the following equation:

$$\alpha = \cos^{-1}\left(\frac{l^2 + d_f^2 - d_t^2}{2ld_f}\right), \tag{3}$$

where $d_t$ is the distance from the pivot to the Origin; $l$ is the length of belt, it can be calculated from the rotation angle of the motor shaft. The detailed view of the FlexTorque is presented in Fig. 6.

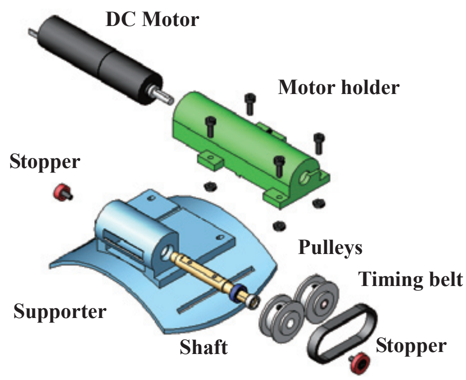


Fig. 6 3D exploded view of driving unit of FlexTorque.

Each unit is compact and light in weight (60 grams). This was achieved due to the use of plastic and duralumin materials in manufacturing the main components. The Supporter surface has concave profile to match the curvature of human arm surface (Fig. 7).

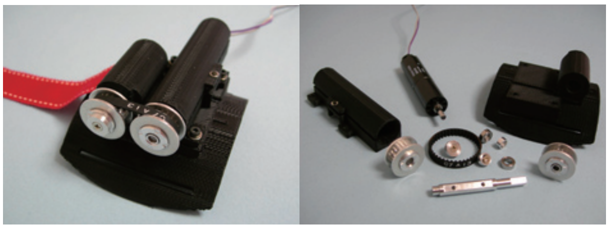

Fig. 7 Driving unit of FlexTorque.

In the case of collision, the limb must be at rest. In such a case, the net torque produced by the muscles is opposed by another equal but opposite torque $T_{load}$. The vibration of the human arm (e.g. simulation of driving the heavy truck) can be modeled through alternate repeatable jerks of torque of antagonistic motors. Thus, operator can perceive the roughness of road surface.

The FlextTorque enables the creation of muscle stiffness. By contracting belts before the perturbation occur we can increase the joint stiffness. For example, during collision of remote robot with moving object the tension of the belt of one driving units drops abruptly and the tension of the belt pulling the forearm in the direction of the impact force increases quickly.

The essential advantage of the structure of FlexTorque device is that heaviest elements (DC motors, shafts, and pulleys) are located on the part of upper arm, which is nearest to the shoulder. Therefore, operator's arm undergoes very small additional loading. The rest of components (belts, belt fixators) are light in weight and do not load the operator's muscles considerably. We propose to use term "Karate Haptics" to such kind of novel devices because they allow presenting the forces to the human arm without using additional interfaces in the human hands.

The developed apparatus features extremely safe force presentation to the operator's arm. While overloading, the belt is physically disconnected from the motor and the safety of the human operator is guaranteed. The FlexTorque also provides gravity compensation to simplify the teleoperation tasks.

## 3. DEVELOPMENT OF THE ERGONOMIC TACTILE DISPLAY BraTact

When it comes to the contact presentation on the human arm, tactile displays are preferable to force-feedback devices. They can convey contact cues [8], direction, and distance information. Recently, haptic gadgets displaying information on a large area of the human body are gaining increased attention by researchers. In [9], reconfigurable, wearable system TactaVest for delivering vibro-tactile stimuli is presented. It can be seen from the papers presented above that, typically, the huge amount of actuators are arranged in regular grid pattern. It should be mentioned here, that heavy tactile display placed on the arm surface degrades the mobility and increases joint muscle loading. Therefore, our objective was to find out the approach to effective presentation of tactile information.

Chen *et al.* [10] examined the human ability to localize a single vibration source on dorsal and volar sides of the forearm near wrist. An important finding was that on average only 4 tactor locations could be correctly identified on both sides of the wrist.

The developed tactile bracelet **BraTact** (**Bra**celet with **Tact**ors) incorporates six vibration motors with holders linked by elastic band. To enhance the localization ability, we arrange the tactors in a zigzag pattern (Fig. 8).

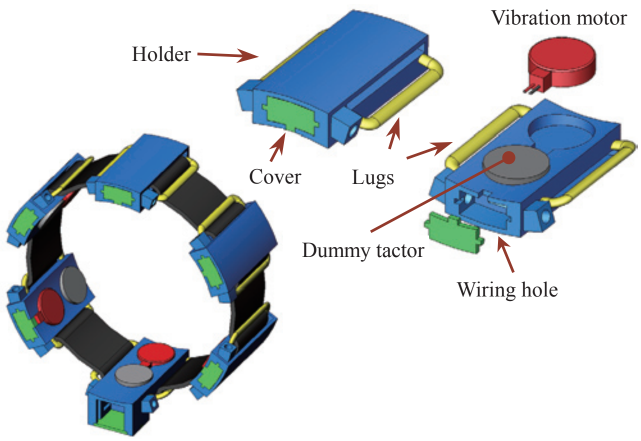


Fig. 8 3D model of tactile display.

The inner surface of the holder has concave profile to match the curvature of human arm surface. The designed tactile bracelet is shown in Fig. 9.

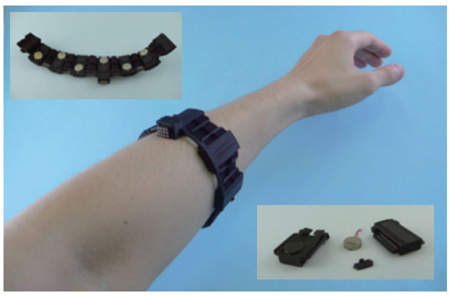

Fig. 9 Tactile display BraTact.

The small flat coreless vibration motors FM34F with diameter of 12 mm and thickness of 3.4 mm produce tactile stimulation on human skin.

## 4. USER STUDY METHODOLOGY

*Apparatus.*

The developed tactile display BraTact was used to present the shape, and stiffness of object. The smallest participant's forearm circumference was 21 cm, so the distance between tactors always was 3.5 cm or more, i.e. larger than a single receptive field (about 2.5 cm).

*Participants.*

A total of 5 males and 1 female with no previous knowledge about experiment were examined. Their age varied from 23 to 31. None of the subjects reported any sensory difficulties.

*Procedure and Stimuli.*

**Object shape presentation.** Object shape information is important for operator. While colliding, the objects with smooth shape attenuate the impact forces. Thus, knowledge of object shape can improve performance of motion planning in cluttered environment. The intuitive approach of representation of simple object shapes (circle (Pattern A), rectangle (B), triangle (C)) and shape primitives (arc (D), line (E), point (F)) is presented in Fig. 10. The dashed ovals depict the active tactors.

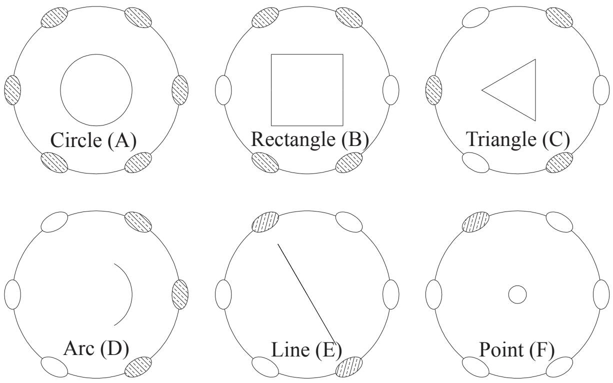


Fig. 10 Tactile presentation of the object shape.

*Dynamic Shapes Experiment* was aimed at presenting the shapes in a more transparent manner. The duration time of tactor activation for all shapes was the same - 2 sec. For round, rectangular and triangular shape, the tactors were activated one by one in counter-clockwise direction. This allows the human to draw in his mind the path represented by tactor. The arc was presented by simultaneous activation of all three tactors, but with time-varying intensities with duration of 2 sec. Moreover, intensity level in the middle tactor was larger than in neighboring ones. To draw the line, we tried to reproduce the apparent motion illusion. For that, two tactors were activated simultaneously but with opposite time-varying intensities levels. That is, when the first tactor had the maximum vibration intensity the opposite tactor had the lowest intensity and vice versa. The point was presented by activation of single tactor with ramp signal.

**Stiffness presentation.** In *Static Stiffness Experiment* all tactors were activated simultaneously with the same intensity level of 2 sec. duration. Five vibration intensity levels (Level 1 (167 Hz) (Pattern A), Level 2 (188 Hz) (B), Level 3 (208 Hz) (C), Level 4 (229 Hz) (D), Level 5 (250 Hz) (E)) representing object stiffness from very low rate to very high were chosen. The darkness level of gray color in Fig. 11 represents the vibration amplitude level.


Fig 11. Tactile presentation of the object stiffness.

In *Dynamic Stiffness Experiment* all tactors were activated simultaneously for given level but with time-varying intensity. The time-dependent pattern was chosen to represent the contact point motion during contact transient (when we collide with stiff object our arm immediately stops moving forward). The stiffest material, aluminum, was presented as short ramp impulse with duration of 0.3 sec. The less stiff material the longer duration and smaller amplitude of impulse were presented to human's forearm skin. To mimic nonlinearity of the sponge material, the sine wave pattern was presented with duration of 2 sec.

The experiment procedure is as follows. To mask auditory cues of the tactor vibration, subjects wore headphones producing pink noise of 65 dBA. They were asked to sit down at the table and grasp vertical stick at the edge of the table to establish static reference position. Subjects were informed that the experiment aimed at testing their ability to discriminate between various patterns. All the participants were given 18 trials practice sessions before experiment for object presentation and 15 trials for stiffness presentation.

In total, 30 stimuli (6 patterns were repeated 5 times in a random order) were presented during object shape discrimination experiment and 25 stimuli (5 patterns were repeated 5 times in a random order) for object stiffness recognition experiment. After each stimulus, the subject marked the table cell corresponding to the pattern had been detected.

## 5. RESULTS AND DISCUSSION

The results of user study are listed in Table 1 - Table 4.

Table 1 Group mean percentage of recognition of shape in dynamics.

| Group Mean Percentage, % | Subject Response | | | | | |
|---|---|---|---|---|---|---|
| Actual Pattern | A | B | C | D | E | F |
| A | **100.0** | 0 | 0 | 0 | 0 | 0 |
| B | 0 | **83.3** | 13.3 | 0 | 0 | 3.3 |
| C | 0 | 3.3 | **96.7** | 0 | 0 | 0 |
| D | 3.3 | 0 | 0 | **73.3** | 10.0 | 13.3 |
| E | 3.3 | 3.3 | 3.3 | 3.3 | **86.7** | 0 |
| F | 0 | 3.3 | 0 | 0 | 3.3 | **93.3** |

Table 2 Group mean percentage of recognition of shape in static condition.

| Group Mean Percentage, % | Subject Response | | | | | |
|---|---|---|---|---|---|---|
| Actual Pattern | A | B | C | D | E | F |
| A | **60.0** | 26.7 | 6.7 | 3.3 | 3.3 | 0 |
| B | 33.3 | **26.7** | 26.7 | 3.3 | 10.0 | 0 |
| C | 10.0 | 33.3 | **43.3** | 0 | 13.3 | 0 |
| D | 0 | 3.3 | 6.7 | **76.7** | 10.0 | 3.3 |
| E | 0 | 10.0 | 20.0 | 16.7 | **53.3** | 0 |
| F | 0 | 0 | 0 | 0 | 3.3 | **96.7** |

Table 3 Group mean percentage of recognition of stiffness in dynamics.

| Group Mean Percentage, % | Subject Response | | | | |
|---|---|---|---|---|---|
| Actual Pattern | A | B | C | D | E |
| A | **100.0** | 0 | 0 | 0 | 0 |
| B | 0 | **80.0** | 13.3 | 6.7 | 0 |
| C | 0 | 16.7 | **73.3** | 10.0 | 0 |
| D | 0 | 0 | 20.0 | **70.0** | 10.0 |
| E | 0 | 0 | 0 | 3.3 | **96.7** |

Table 4 Group mean percentage of recognition of stiffness in static condition.

| Group Mean Percentage, % | Subject Response | | | | |
|---|---|---|---|---|---|
| Actual Pattern | A | B | C | D | E |
| A | **73.3** | 20.0 | 6.7 | 0 | 0 |
| B | 13.3 | **50.0** | 16.7 | 20.0 | 0 |
| C | 0 | 16.7 | **50.0** | 20.0 | 13.3 |
| D | 0 | 0 | 23.3 | **53.3** | 23.3 |
| E | 0 | 0 | 6.7 | 23.3 | **70.0** |

The ANOVA results revealed that it was significantly easier for participants to recognize stiffness of materials B ($p=0.001<0.05$) and E ($p=0.04<0.05$) during Dynamic Condition than in Static Condition. Shape patterns A, B, and C were significantly easier to recognize during Dynamic Condition than in Static Condition ($p=0.006<0.05$, $p=0.002<0.05$, and $p=0.007<0.05$, correspondingly). The important point is that the recognition rate of the line presented by apparent motion illusion was much more higher than that of line presented in *Static* mode. Based on this evidence, we can use this effect to draw more complex shapes.

## 6. CONCLUSIONS AND FUTURE WORK

The increasing complexity of tasks performed by teleoperation requires to deliver and to display tactile information to the human operator effectively in order to ensure safe and efficient interaction with environment. The sensory system of the developed slave robot supports the local admittance controllers generating compliant motion with information on exerted force.

We developed a novel haptic interface FlexTorque that enables realistic physical interaction with Real (through teleoperation system) and Virtual Environments. The main features are: (1) it does not restrict the motion of the human arm, (2) it has wearable design, and (3) it is extremely safe in operation. This haptic display can find the future applications also in Virtual Reality systems for realization of realistic physical interaction, haptic communication, and presentation of weight and stiffness of object to the user. In the future we will conduct thorough user study of the developed haptic display FlexTorque.

The tactile display BraTact supporting the presentation of tactile information by means of the bracelet with tactors was developed. The results of the user study revealed that the Dynamic mode of presentation of the object properties was more intuitive, and, therefore, resulted in very high level of discrimination accuracy. The future step is elaboration of the concept of "*Dynamic tactile drawing"*, when graphical information is presented by tactile patterns generated discretely in time.

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