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Abstract

Body-grounded kinesthetic haptic devices can provide cues for movement in multiple degrees of freedom by exerting forces directly on users, as in dexterous robot teleoperation tasks. However, these haptic devices have limited workspaces, can destabilize a teleoperation control loop, and can be expensive. Portable haptic devices can approximate the sensations of a kinesthetic device by exploiting diverse human sense of touch principles without these shortcomings. Our goal is to analyze the feasibility of hand guidance (HG) using tangential force stimuli. Here we reveal and quantify users' interpretation of simultaneous tactile stimulation (STS) applied to multiple finger pads of the same hand. We completed an extensive experiment on different users to reveal a maximum number of understandable cues which can be used as movement commands for HG. As expected, many tactile stimuli tested were meaningless for users, but a few could be clearly interpreted — we call these "intuitive movement cues". For the experiment, we designed a device that can be held in the palm and exerts tactile stimuli to the user's finger pads on the thumb and index fingers, or the thumb and middle fingers. We performed two studies in which we identified the extent of salience of different movement cues. In particular, commands to redirect the hand position and orientation in four axes: moving forward/backward, wrist twisting right/left (rotate clockwise/counter-clockwise), moving right/left, and wrist tilting up/down (rotate upwards/downwards). The results revealed that this approach provided 7 intuitive directional movement cues for relative HG in 3D space. The proposed HG principle is promising for applications such as robotic surgery training, laparoscopic training, and needle insertion training, during which surgical trainees must learn dexterous hand movements involving motion paths. There are many applications for 3D movement guidance outside the medical domain that could benefit from this haptics technology, including training for precise manipulation and assembly tasks, augmented teleoperation, and communication during shared control in collaborative human-machine systems.

key words— human-machine communication, cutaneous feedback, skin-stretch, simultaneous tactile stimulation

1 Introduction

Hand guidance (HG) via portable haptic feedback (HF) devices may boost confidence to achieve practical independence of surgeon residents at the end of their studies — a sought-after goal which is not currently fulfilled [1], [2]. Our ultimate aim — which is beyond of this publication — is to develop a robotic surgery training system (i.e. a virtual surgical mentor) to be used from the early stages of medical training. This training system should provide a way to perform HG in multiple directions, or degrees-of-freedom (DoF), on a budget.

Body-grounded kinesthetic HF devices have been successfully used for training in other domains, e.g. for complex handwriting of Asian and Arabic texts [3]–[5] or car driving simulations [6], [7]. However, the use of HF devices in surgical training is not well studied. In particular, minimally invasive surgery (MIS) and robotically-assisted MIS require technical proficiency in tasks for which surgeon trainees spend substantial time repeating surgical gestures.

To date, there is scattered evidence that HF helps improve safety in robotic surgery tasks. Most commercial surgical robots only use virtual fixtures, thus limiting haptic information to indicate no-go zones. In surgical training, there are only a few cases where HF helped speed up the learning process [8]–[11]. The difficulty of testing HF systems in the operating room (OR) could partly explain this dearth of evidence. However, it is easier to test HF systems outside the OR, in a non-clinical training setting.

Our haptics research is geared towards understanding why experiments, or haptic devices, have not yielded the anticipated results. We aimed to induce the feeling of multi-DoF "virtual pulling forces and torques" for HG from handheld devices. In prior work [12], we designed a simple device to send 4 movement commands to the user through simultaneous tactile stimulation (STS) on two fingers (forward/backward movement and left/right wrist twisting), but there was some inconsistency in the identified direction cues. It highlighted the potential of a simple haptic device to provide guidance in more DoFs [13].

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Therefore, we explored two directions: (1) designing a more complex HG device that could provide 4-DoF [14]; and (2) identifying as much as possible clear directional cues from the simple HG device (nearly 4-DoF).

This paper focuses on gaining a deep understanding of STS perception. We explored a broad range of STSs in 3 human subject experiments. The results of each experiment enabled us to relate movement cues interpreted by users to specific stimuli exerted on fingers — determining which HG command can be reliably communicated.

In addition, we investigated whether the interpretation of HG is dependent on the pair of fingers stimulated. The reason of this is that surgical robots, like da Vinci® or Hugo®, are tele-operated by using 2 possible grasping (thumb-index or thumb-middle).

The paper organization is: Section 2 outlines relevant terminology. Section 3 provides background of related haptic research. Section 4 presents the materials. Section 5 points out key experimental results of a prior prototype, which motivates this paper. Section 6 describes the setup and test protocol for our human subject experiments. The results are reported in Section 7, discussed in Section 8, and Section 9 is the conclusion of this research work.

2 Harmonization of terminology

Our haptic device is a tactile stimuli source that provides *movement cues* (e.g. pulling up, pushing forward). In our experiments, participants were exposed to a broad range of tactile stimuli and reported the sensation felt for each stimulus as a direction. Some of these sensations were manifested by participants like *movement cues* applied on their hands − felt as an invisible pull/steering forces.

Cue salience: is a within-subjects or single subject measure of the extent of participant certainty about the feeling, or sensation, of a specific *movement cue*. For a given user, a single *movement cue* can be induced by different STSs with different levels of confidence. In this study, if the same *movement cue* is evoked for the same set of STSs over 80% of trials, we describe it as *high salience*.

Intuitive movement cue: is the match between a *stimulus* sent (STS) and the same sensation felt among different users — the same hand *movement cue*. This agreement between users means that a particular *movement cue* is *intuitive* (i.e. *high salience*) for all users and could thus become a HG command. An *intuitive movement cue* is hence perceived by people as a "virtual force" indicating how to redirect their hand in a certain orientation in 3D space.

In Figure 1, we illustrate and named the different zones of the finger to stimulate in this study. We took terminology commonly used in specialized fields such as biomechanics, physiology and neuroscience [15]–[19].

3 Related Research

3.1 Related haptic devices

Vibrational actuators [20] are compact, robust, and well suited for delivering discrete vibratory signals. For guidance applications, an array of actuators are triggered in a rapid temporal sequence, thus giving the sensation of motion. However, human mechanoreceptors that detect vibrations have large receptive fields, so several actuators are needed to deliver a high variety of stimuli for hand guidance [21]–[24]. In addition, the meaning of distributed stimulus patterns must be learned.

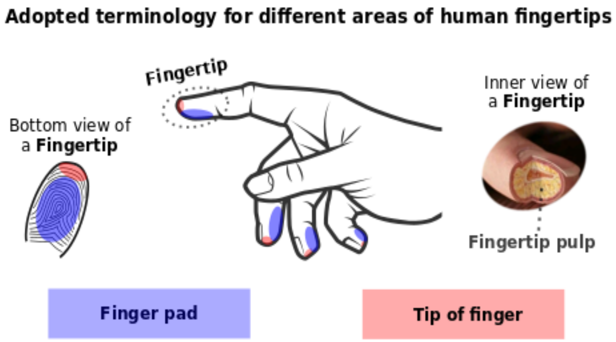

Figure 1. The colored areas indicate the proposed terminology for different human fingertip zones. The English terms illustrated here aim to harmonize the terminology used for HF device stimulation.

Electrocutaneous stimuli are patterns of small electric currents [25] that stimulate cutaneous nerve fibers of the afferent nervous system. In [26] these were used for communicating vector information on a plane by applying them on the three phalanges of three fingers (index, middle and ring). The 3x3 array allowed for discern cues regarding both the direction and magnitude on the plane of the hand without other kinds of stimuli.

Lateral skin deformation, particularly tangential strain on glabrous skin, has been studied to render virtual textures [27]. The HF device exerts saltating stimuli produced by an array of piezoelectric pins providing small amounts of localized skin stretch to communicate direction. A single actuator can be applied to a user's finger pad. Yet the HF device is large-sized, resembling a dot-matrix print head. A dual pin actuator for rotational skin stretch deformation (no slip) was evaluated on hairy skin of the forearm [28]. Skin adhesive was used in these experiments to minimize actuator slip. These experiments were conducted with a bench top placed skin stretch device.

Body-grounded tactile actuators, or wearable HF devices, were designed and compared in [29], [30]. Researchers conducted a comparison between 4 different devices and stimulation principles. They reported shorter reaction times of the participant responses to the only device that does not require discernment of the sense of rotation (i.e. without mental load to interpret the cue). They focused on the achievement of a wrist rotational task (1-DoF).

Frictional forces were studied in [31] — similar stimuli to those of our HF device but at single actuator level, so no STS. In this work, the proposed device exerted tangential frictional force through a leadscrew pressing against the finger pad of the index. They successfully communicated 2-DoF using two orthogonal finger placements. The findings of [31] relevant to HF for HG are: (1) alternation between static and kinetic friction enhanced the directional sensation; (2) the device better conveyed left–right cues when the cylinder rotation direction dominated the sensation; and (3) the device better conveyed the forward–backward dimension when the thread motion direction dominated.

Shear force exerted on the skin (tangential skin deformation and normal finger pad displacement) has been widely used in large rehabilitation devices because it speeds up motor learning without visual attention [32]. In [33] a fingertip-mounted device that laterally deflected the finger pad succeeded in conveying directional navigation cues in 1 DoF.

Skin deformation applied to human fingers [34]–[37] suggested that these stimuli could communicate more than four directions (> 2-DoF). A communication accuracy analysis [38] showed that the magnitude and speed of stimuli positively contribute to correct direction identification (i.e. longer displacements and faster speeds make movement cues more intuitive). However, all these studies assessed the effects solely on the index finger, and few studies have focused on the thumb [39].

Finally, recent wearable haptic devices [40], [41]–[45] stimulate more than one fingertip. They have investigated HG, sensory substitution, and force feedback in teleoperation. The authors of these studies assessed the reliability of directional information, reaction times, and tactile salience stimuli thresholds or tactile just noticeable differences (JND) [46]. Concerning HG, STS was used in a thumb-index back-to-back setup [40] that successfully communicated 5-DoF, however they only explored STSs of same magnitude (same actuator displacement for both fingers) — hereinafter symmetric STS.

3.2 Specific understanding of haptic perception

Cutaneous frictional cues (e.g. surface skin strain and stretch) are interpreted by the somatosensory system at three levels [20]: (1) the various cutaneous mechanoreceptors, like Ruffini endings for detection of innocuous tangential force stimuli on finger pads [18], [20]; (2) the spinal cord, through dorsal horn interneurons and dorsal horn projection neurons [20]; and (3) the brain, in the postcentral gyrus of the parietal lobe.

Studies carried out on the forearm skin showed that humans' ability to notice the direction of a moving tactile stimulus depends on parallel processing of two types of sensory information [47], [48]. The first type concerns the sequential order of activation of adjacent mechanoreceptors (spatiotemporal information). The second type of sensory information consists of tangential skin deformation or skin shear forces (information on friction induced changes).

Experiments on hairy skin, with < 8 mm displacements revealed that stimuli causing frictional contact have more salience than those that only activate the spatiotemporal system [49]. The accuracy with regard to tangential skin deformation was identified down to 0.32 mm more than 80% of the time. Moreover, it was demonstrated that information from stretch sensitive receptors located at remote distances (> 15 mm from the stimuli locations) was effectively used for directional sensitivity [50].

Data-driven research conducted on finger pads [51], [35], [38], [39], identified cue salience thresholds; range of stimuli forces; effects of multi-pin stimulation; effects of speed, skin displacement; and different fingertip restraints on movement cue salience. It is noticeable that multi-pin stimulation with no slip on the same finger pad showed no difference in inducing a movement cue [35].

On perception of tangential skin displacement, comparable cue salience between skin indentation and skin tangential displacement is achieved with at least 1/3 less displacement for tangential tactile stimuli [51]. When restraining the finger against a tactor, successful interpretation of cue direction was found to be directly proportional to the speed and displacement of tactile stimuli, with maximal accuracy achieved from > 1 mm/s speed and > 1 mm displacement [38]. Constraining of part of the finger pad tends to decrease direction discrimination accuracy [39]. Tactor diameter does not seem to alter accuracy in [39]. Studies on finger pads of the thumb and index fingers showed that the selection of a proper aperture size enabled good movement cue accuracy, but differences between digits were noted for unknown reasons (with the same aperture diameter the smaller fingers performed better but only for the index fingers) [39] — these results highlighted the need to conduct investigations using different fingers.

In view of this prior understanding, our research hypothesizes that tangential force stimuli applied on finger pads are likely processed at the first and second levels of the somatosensory system. As the processing is done before reaching the brain, STS cue interpretation would involve tactile primitives — feelings shared between different people. If this is true, these tactile movement cues will require little mental load.

4 Shear force based portable haptic device

From a former prototype [12], we engineered a simple, inexpensive, and easy to produce HG device. The device consists of a pair of servomotors (MG90S TowerPro, stall torque of 0.176 N· m with 4.8V) mounted in a 3D printed handle, as shown in Figure 2.

Each motor can rotates a lever arm in a variety of angles (displacement magnitude) and two in directions. The tips of the lever arms contains a textured rubber which acts as a contact interface with user's finger pads. Hereinafter these tactile actuators are denoted as tactors.

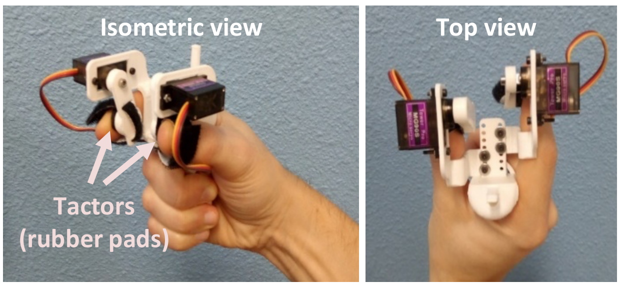

Figure 2. Different views of the portable HG device in the thumb-index grip style. Views show the lever arms of each servomotor that jointly perform STS on the thumb and index *finger pads*. The top view better depicts the adjustable position of the actuators on the handle to adapt the device to users with different hand sizes.

One tactor stretch the user's finger pad of one finger, as illustrated in Figure 3. The tip of each lever arm is fastened to the distal phalange with Velcro® strip to maintain contact between the finger pad and the tactor. This type of attachment is used in commercial robot-assisted surgical systems, thus it enable to hold the device with 2 different grip styles (thumb-index or thumb-middle fingers).

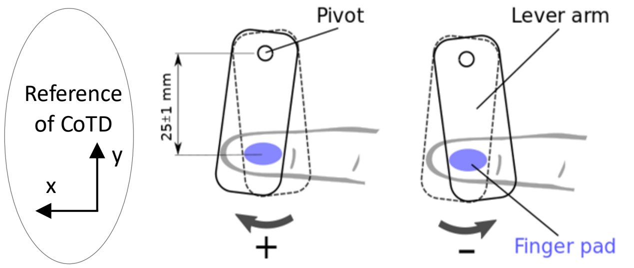

Figure 3. Scheme for one tactile actuator or tactor. The 2 directions of movement describing a short semicircular arc. For clarity, the rubber interphase is not shown, but it is the contact interface with the *finger pad*. The center of the region of the skin surface in contact with the tactor is called center of tangential displacement (CoTD).

The working principle of our haptic device is to produce tangential shearing forces exerted on the user's finger pads. This happens when the tactor move away certain amount from the central/initial resting position. When the device moves both tactors simultaneously, two fingers are stimulate (STS — colored arrows in Fig. 4), which induces an intuitive directional force on the user's hand (movement cues — white arrows in Fig. 4).

These intuitive directional forces perceived by the user, communicate effectively hand movement commands through the sense of touch alone. In Figure 4, the side views illustrate the command movements in 2-DoFs (forward/backward translational movement, and wrist up/down rotational movement), while the top views illustrate the command movements in other 2-DoFs (left/right wrist rotational movement, and left/right translational movement).

Figure 5. Left: forearm resting position in our experimental setup. Right: example of forearm resting position during robotic-assisted surgery training.

Test campaigns are automated through a computer, which sends the set point values to a microcontroller (Arduino Nano) that timely manage the displacements of tactors. The servomotors used have a stall torque ($0.176\ N\cdot m$ with 4.8V) that empirically proved to be suitable for the application. Finally, the weight of the device is 67 grams that facilitated its use during long tests.

5 Clue that non-evident simultaneous tactile stimulations may render new movement cues

Several experiments were conducted to understand the cues that can be clearly provided from this kind of device. Table 1 provides details on the different stimuli and other experimental considerations of our prior work [12], which investigated the use of symmetric STS. Also, Table 1 is used to compare the features of the 3 test sessions conducted in this paper.

From raw data of [12], sporadic responses from users gave us a clue of a possible unattended perception effect. The concept is that at least 2 diverse movement cues may be rendered using the same circular motion of tactors (but only different in magnitude). This quite interesting and worth investigating because, if this is true, with a reduced number of motors would be possible to transmit several movements cues.

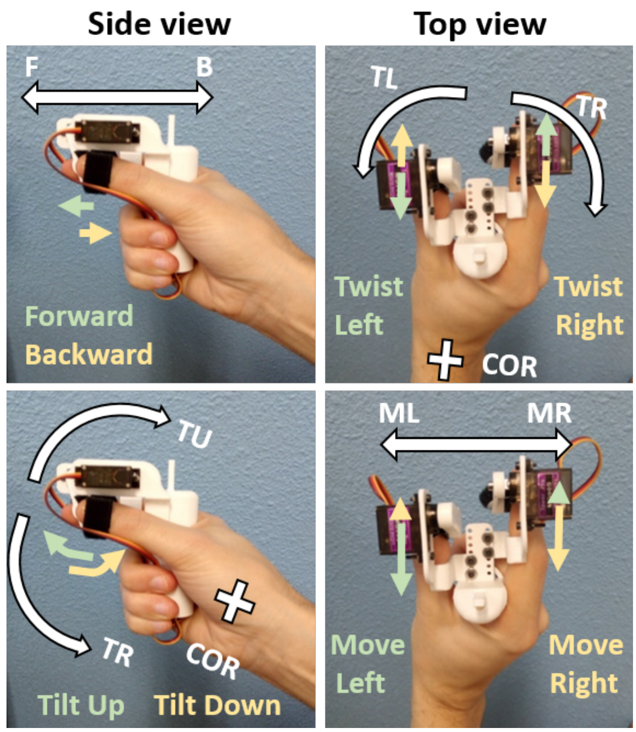

Figure 4. Different views of the portable HG device in the thumb-index grip configuration. The 4 pictures illustrate the 4-DoF of the induced hand movements shown by the white arrows, and the center of rotation (COR). The small arrows (green and yellow) indicate the STS on the *finger pads* of the pair of fingers. The arrow size indicates the movement magnitude. A video describing the device is included as supplementary material and available ***here***.

Table 1. Main features of Tests 1 and 2 for cue salience identification. A prior exploratory test is presented for comparison.

	Exploratory test [12]	Test 1a	Test 1b	Test 2
Objectives	· Explore commands in two different DoF · Test protocol definition	· Explore new DoF: right/left translation · Study actuation in different finger pairs · Enhance the test protocol		· To complete the 4-DoF identification · To assess movement cue intuitiveness
Participants	8	7	7	14
DoF studied	3	2	2	2 ($\neq$ to Test 1)
Stimuli	24 (10x)	72 (10x)	72 (10x)	72 (10x)
Commands	6	4	4	4
Possible answers	6	4 + unsure	4 + unsure	8 + unsure

6 EXPERIMENTAL METHODS

Three tests were planned. Test 1a and 1b investigated two aspects: (1) the use of a variety of STS to induce a new DoF not found before [12]; (2) comparison of the effects of the HG device when it is used with two different finger pairs. Test 2 explored the use of asymmetric STS to explore the possibility of enhancing the cue salience of the movement cues preliminary observed in [12].

The participants recruited for the experiments (n=18) gave informed consent. No participants reported any known neurological or sensorimotor deficits concerning their sense of touch (i.e. due to accident or illness). Participants were recruited with no previous experience with haptic devices. The participants were classified as having small or big hands — handgrip diameter $\leq$ 4 cm (n_s=12) and > 4 cm (n_b=6), respectively, in order to carry out the tests using the same device size setting in each group. The gender ratio was almost 2/3 (F=7, M=11).

The research addressed between-subject (i.e. how intuitive is a movement cue?) and within-subject questions (i.e. which are feasible movement cues?; how much salience does each movement cue have?). The experimental design was geared towards minimizing the learning effects across conditions because not all participants carried out the two test sessions (more details in Table 2).

The experimental setup for the experiments involved a laptop computer connected to the device (Section 4) that was held in the participant's right hand. Participants were instructed to mimic the arm resting position used by surgeons in the master console of da Vinci robot, as shown in Figure 5. Moreover, headphones and a carton box were used to mask visual and auditory *cues* of the device in order to avoid cross-modal perceptual facilitation.

Special attention was focused on participant arm placement (e.g. free elbow and wrist while a single segment of the forearm was used for resting), for two reasons: (1) we tried to mimic the arm positioning used in robotic surgery training; and (2) in pilot tests we observed that the pressures exerted on the elbow during the experiment could induce tactile sensations that interfered with the movement cues.

During the experiments, participants sat in a chair facing a table with the computer. They held the device with their right hand placed inside a cardboard box in order to hide the visual cues. Participants were listening to music through headphones to hide possible auditory cues and they interacted with the computer via their left hand (keyboard) and eyes (screen).

Table 2. Distribution of the 18 participants between the two test sessions. (*) One participant did not complete the full trial (4-day and 2-day commitment for Tests 1 and 2) so we excluded her data from the analysis.

	Participants in	Gender	Test 1	Test 2
	1 test session	F	1*	5
		M	3	5
	2 test sessions	F	1	
		M	3	
Total*			7	14
Gender ratio*			1/6	3/4

In the experiment, the participants triggered a stimulus from the device through a keyboard. Participants responded to movement cues they felt by pressing a number key associated to the possible answers (5 or 9 answers for Tests 1 or 2, respectively). During the experiments, participants were obliged to confirm each answer for each stimulus. Before confirming, they could replay the stimulus and give a new answer if desired. Participants were told to answer "unsure" if they did not understand the sensation perceived after three attempts. This choice was added in order to enhance users' confidence when interpreting each kind of stimulus, while avoiding the collection of false answers.

The data collected during all test sessions was analyzed relative to two aspects: (1) movement cue identification; and (2) frequency of occurrence of each movement cue. These two aspects were studied for each of the 72 different tactile stimuli, i.e. the STS applied on a pair of finger pads corresponding to the fingers of the right hand.

6.1 General test protocol for the identification and assessment of hand *movement cues*

The test protocol described below contains all the stages in each of our studies and our recommendations for reproducibility of the haptics experiment concerning STS.

Explanation of the research goals to the participants: justify the need for participant collaboration and the possible impact of her/his contribution; provide a brief explanation of the main objectives of the experiment (e.g. transmission of hand movement commands to the participant, through her/his sense of touch), orally and using their mother language if possible.

Presentation of the experimental setup and its requirements to the participants: discuss the reasons for the layout of the experimental setup and explain what will happen; specify the requirements of the experiment and highlight the participant's role (e.g. maintain the forearm in a specific resting position; maintain the hand hovering the table with the device during the experiment; avoid seeing or hearing the device in action; the way to submit answers; how to proceed when it is necessary to replace the prior submission in case of a mistake).

Demonstration of the experimental process with the researcher's hand. This familiarization step had a dual aim: to show the participant that use of the device has no inconveniences; and to enable the researcher to review the proper procedure for the test session (e.g. reviewing the hand movement cue answering process; reviewing hand and forearm placements).

Requesting informed consent from participants. Before the experiment began, we asked participants to summarize her/his understanding about the experiment in his/her own words. Then we stated the approval of the LIRMM ethical review board and briefly explained the treatment of the data collected (e.g. data security and anonymization), and then asked to give their informed consent.

Hand morphology and relevant personal data collection. We obtained several anthropometric measurements of the hand. We found that it was important to measure the participants' *handgrip diameter* for the purpose of hand-size classification and adjusting the size of our device (top view of Figure 4). We followed the methodology described by [56], which is based on the NASA-1024 (1978) measurement guidelines. These guidelines require that a calibrated cone be initially grasped by the participants. We provide the files of the 3D printed cone and complementary information used here [52].

Then we asked participants about any atypical hand features (e.g. scars; past finger wounds). Finally, we requested personal information to guarantee the participants' safety in our experimental setup (e.g. implantation of a pacemaker) and information relevant to the research (e.g. age; gender; hobbies that require hand-eye coordination; amount of experience in these hobbies; dexterity or hand skill self-assessment).

Placement of participants in the experimental setup. Each participant sat down comfortably facing a desk with a laptop computer and the device (Picture 5). The researcher adjusted the device to the participant's hand size and placed it in her/his right hand. Tactors of the device were placed in a neutral position for this participant (nearly straight down from the motors). Then the device was hidden from participant's view (e.g. by enclosing it in a cardboard box) and the armrest was adjusted for participant's comfort.

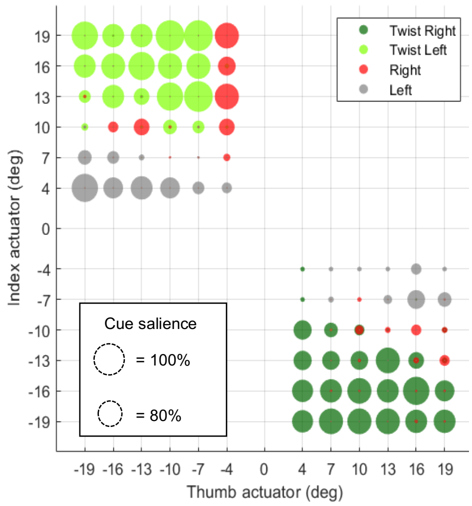

Figure 6. Hand *movement cues* identified in Test 1a. Participants used the thumb-index finger pair to grab the device. They were obliged to choose between 2-DoF and the "unclear" feeling.

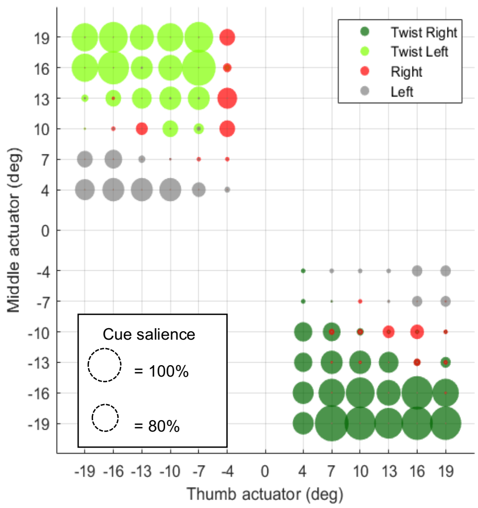

Figure 7. Hand *movement cues* identified in Test 1b. In this test, participants used a different grip style to hold the HF device with the thumb-middle finger pair.

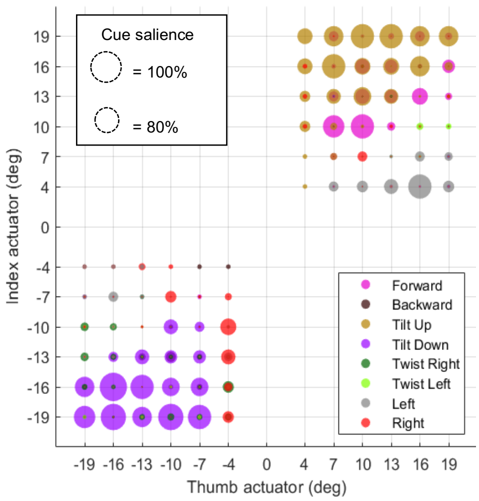

Figure 8. Results of the *movement cue* exploration in Test 2. Participants used the thumb-index finger pair to grab the device. Participants were free to answer as they wished.

Familiarization of participants with the tactile experiment. An initial sample trial was assisted by the researcher to confirm that the participant was comfortable with the procedure. During the sample trial, the researcher recalled the list of predefined answers — which varied between test sessions, and prompted the participant to use the resubmission procedure for a wrongly typed answer for familiarization. When the participant said that she/he was ready to start the real experiment, we proceeded to mask possible auditory cues from the device by placing headphones over the participants' ears playing the participant's desired music.

Launch of the automated test session. Throughout the experiment, pseudorandom stimuli sequences were executed to avoid participant learning effects (Table 1). There were programed time breaks during the experiment. The participant was free to release the device and take break of up to 15 min. The researcher assisted the participant with proper placement of the device before continuing the experiment.

Note: Participant engagement in long test sessions. Participants got bored during long experimental trials (e.g. about 90 min.), even when they were allowed to listen to their desired music. We actually had to re-perform one trial because the participant had fallen asleep during the experiment. We thus suggest not listening to relaxing sounds or conducting experiments just after lunchtime.

Retrospective survey. When participants finished the test trial, we discussed her/his impressions of the tactile stimulations and *movement cues* felt. The researcher specifically recorded ergonomic issues with wearing the device, possible improvements in the test procedure or the device, and remarkable comments or events that occurred.

Complementary measurements: Tracking of involuntary hand movements. We measured participant's hands movements in 3D using a certified medical field generator and a magnetic tracker probe from Ascension Technology (Burlington, VT, USA). This instrument generates an intense magnetic field (i.e. pulsed quasi-static direct current fields) that makes it impossible to test the device with participants with a pacemaker implant. For the best signal-to-noise ratio, we shielded the measurement workspace with aluminum film from 5 directions — the shielded box was behind the smaller one (Figure 5).

6.2 Test 1: exploring various STS on two finger pairs (thumb-index and -middle)

Test 1 focused on extensive movement cue identification in two grip styles involving the thumb, index, and middle finger pads. The effects on two finger pairs of the right hand were studied: thumb-index and thumb-middle.

Contrary to our pilot test where symmetric STS was investigated [12], Test 1 included asymmetric STS (different motion magnitudes applied to each finger). The total number of stimuli was increased from 24 to 72 (Table 1), which increased the test time per participant. To prevent fatigue, we partitioned the test session in 2 days (Test 1a and Test 1b), thus allowing us to detect the salience of movement cues using the full tactor movement range.

During Test 1, participants provided answers on movement cues under 5 options: unclear; two wrist twisting movements (twist right/left); and two lateral translation movements (move right/left). 72 different STS (with angular displacements: $\pm 19^o$, $\pm 16^o$, $\pm 13^o$, $\pm 10^o$, $\pm 7^o$, $\pm 4^o$) were applied in a pseudorandom sequence of 360 STS per trial, for a total of 720 stimuli (each stimulus 10x) per grip style.

6.3 Test 2: applying various STS to investigate the confidence of *movement cues*

Test 2 involved extensive movement cue identification (72 different STSs) with one grip style (thumb-index). This test was designed to induce different or complementary DoFs with respect to Test 1. We also assessed the confidence of movement cues, or so-called cue intuitiveness. Low confidence means confusion between two or more movement cues for a given STS.

In this experiment, we did not ask participants to choose between 2-DoF as in Test 1. We just gave the choice of "unclear" plus 8 cases corresponding to 4-DoF. The 9 options of Test 2 were: unclear; four translational movements (forward/backward and right/left); two tilting movements (tilt up/down); and two twist movements (twist right/left).

We did not attempt to send all of these kinds of stimuli movements, but we told participants that all of these movement cues were in the test. The 2-DoF targeted in Test 2 were: two translational and tilting movements (forward/backward and tilt up/down). Our intention was to study the confidence of these movement cues against the remaining ones.

7 Results

In all studies, participants typically chose a direction after triggering the tactile stimulus just 1 or 2 times. Participants who completed both tests spent a total of around 320 minutes of participant engagement through 4 and 2 different and non-consecutive work days. Each test campaign included the use of the device two different days (each test presented a total of 5 times the 72 STSs) to complete a trial.

The device was set for small and big hand sizes. Initially, three participants with hand sizes at the lower boundary of the big hand size (*handgrip diameter* about 4 cm) presented inconsistent results when using the bigger hand setting. Then, we understood that the setting used for these participants was uncomfortable. The hand geometry (i.e. hand anthropometry) of these three users was better suited for a smaller device setting. Therefore, after a few weeks, these three participants repeated the experiments with the device configured for smaller hands. Finally, we obtained consistent results and related these episodes to the fact that the hand posture modulates the perception of touch [53].

To interpret the data collected, in terms of cue salience due to the frequency of occurrence, we defined the *actuation-cue salience map* (Figures 6-8). This map represents several dimensions of interest: (1) the STS required in terms of tactor displacements (the x- and y-coordinates) to induce a specific *movement cue* (the mark colors); (2) the *salience* of a movement cue for each STS (the mark diameter); and (3) how *intuitive* the movement cue is, with a view to it becoming a HG command (the purity of the color mark).

Figures 6 and 7 show the results of Test 1a and 1b for the thumb-index and thumb-middle. The results were similar for stimulations on different fingers, in agreement with [12, 39]. Remarkably, we were able to induce two new *intuitive movement cues* in addition to those demonstrated in [12]. We used the same type of STS but of asymmetric magnitude: right and left. The new sensations are indicated by red circular marks (e.g., {(-4, 13); (-4, 19)}) and gray ones (e.g., {(-16, 4); (-16, -7)}) in both grip styles.

The second quadrant of the maps shows several STS with high *cue salience* to induce three HG commands (e.g. hand moving left/right and wrist twisting left). The forth quadrant contains only important *cue salience* possibilities for twisting right commands. These results enabled us to assess the HG in these 2-DoF.

In Test 2, we addressed the two quadrants in the *actuation-cue salience map* that Test 1 did not address. We focused on the study of thumb-index and differently to Test 1, we did not constrain participants in the number of possible answers (number of possible answers in Table 1). Therefore, movement cues with multiple interpretations appear in Figure 8 as overlaps of tiny circles of different colors (less salient movement cues acts as perturbation).

Regarding Test 2, the first quadrant of Figure 8 presents several STS with high cue salience to mainly induce two-directional commands (e.g. moving forward and tilting up). The third quadrant contains one of the opposite directional commands (e.g. tilting down), while the movement backward command was barely felt by the participants.

7.1 Combining the results of Test 1a and Test 2

From the data of Test 1a and Test 2, the biggest circular marks on the maps for each movement command, defines the displacement of each tactor that generates the STS. These haptic signals (tactile stimuli) produced for the HG device were able to induce *movement cues* among all participants, with at least 80% confidence.

We attempted to transmit 8 directional commands for HG in the 3D space (i.e. move forward/backward, tilt up/down, twist left/right, and move left/right), which correspond to 4-DoF. Our results revealed that 7 commands presented haptic actuation that elicited a salient movement cue or an intuitive cue for the participants — selected at least 80% of the time for at least one stimuli. Our HG device did not succeed in properly indicating a *backward movement cue* to participants (i.e. small black circles located in (-7, -4) and (-4, -4) corresponding to less than 20%).

All participants stated that the movement cues for wrist twisting were the most salient (13.9% of the 72 STS evaluated), as reflected in the results (green colors in Fig. 12) for all combinations of angular displacement of tactors. The salience corresponding to the other movement cues were: tilting (5.5%), left/right movement (3.5%), forward/backward movement (1.4%), with the *unsure cue* (35.4%) getting the highest coverage on the *actuation-cue salience map*.

A summary of the participants' qualitative impressions collected in the retrospective survey is as follows: the STSs linked to wrist twisting were described as a "virtual torque" applied to her/his right hand; the participants ended the experiment with many doubts due to the high proportion of non-salient movement cues (more than 1/3 of test time); participants found that they could sometimes feel the STS of the tactor repositioning to the central position; some participants were able to use this second STS to verify their answer before submitting it.

7.2 Combined results in terms of x-y displacement

The results, as presented in the *actuation-cue salience map,* highlight the potential of this kind of device to provide directional commands to the user. However, as the map is expressed in angular displacement of our tactors, it would be impractical to compare the performance of our HG with respect to devices that employ different tactors. Therefore, we converted the angular displacement of the tactors to the respective the x-y displacements over the *finger pads*. This facilitates comparisons between different type of devices in terms of tangential skin deformation or of skin stretching,
According with the length of the tactor lever arm the center of tangential displacement (CoTD) can be calculated for each finger pad. In our device, the *z component* remained constant at zero because the mechanism did not move in this direction. Table 3 indicates the $CoTD_x$ and $CoTD_y$ (in mm) corresponding to the *STS* of a single tactor. For these displacements, the average tangential speed for quick stimulation movement is 21.6 mm/s and the slow rearmament movement is 5.4 mm/s.

Table 3. Center of tangential displacement (CoTD) of a single tactor expressed in x-y coordinates.

Actuator angle (deg)		4	7	10	13	16	19
Tactor displacement	x (mm)	1.7	3.0	4.3	5.6	6.9	8.1
	y (mm)	0.1	0.2	0.4	0.6	1.0	1.4

Finally, Table 4 presents the CoTD corresponding to the STS of all the movement cues that presented more salience (salience ≥ 80%). This reduced set of tactile stimuli are the *intuitive movement cues* discovered in this research. These findings could be compared against future and previous skin displacement values from the literature (see Section 3.3) —yet these values were mostly given for a single axis. Note that tactor displacement is a circular arc of radio 25 mm.

8 Discussion

The results in the *actuation-cues salience map* highlight that several STS presented *movement cues* met two conditions simultaneously: (1) 100% of the participants reported the same movement cue between them for the same STS; and (2) the movement cue was identified in at least 80% of the trials in which it was delivered to each participant. Considering these percentages, we believe that we have found *intuitive movement cues* (Section 2).

Motivated for an application in robotic surgery, to the knowledge of the authors, this is the first research that studied STS with 2 grip configurations (thumb-index and thumb-middle finger). Thus, we assessed the possibility of using the same device for HG in both configurations.

Table 4. Detail of the 7 *intuitive movement cues* obtained in this study and the simultaneous tactile stimulation required for hand guidance.

Intuitive movement cues found	Simultaneous Tactile Stimulation (STS)					
	Actuator angle (deg)		Displacement in X-Y plane			
			CoTDx (mm)		CoTDy (mm)	
	Thumb	Index	Thumb	Index	Thumb	Index
Forward 1	7	10	3.0	4.3	0.2	0.4
Forward 2	10	10	4.3	4.3	0.4	0.4
Backward	none	none	none	none	none	none
Tilt Up 1	7	16	3.0	6.9	0.2	1.0
Tilt Up 2	10	19	4.3	8.1	0.4	1.4
Tilt Up 3	13	19	5.6	8.1	0.6	1.4
Tilt Down 1	-16	-16	-6.9	-6.9	1.0	1.0
Tilt Down 2	-13	-16	-5.6	-6.9	0.6	1.0
Tilt Down 3	-16	-19	-6.9	-8.1	1.0	1.4
Tilt Down 4	-10	-19	-4.3	-8.1	0.4	1.4
Twist Right 1	13	-13	5.6	-5.6	0.6	0.6
Twist Right 2	10	-16	4.3	-6.9	0.4	1.0
Twist Right 3	16	-16	6.9	-6.9	1.0	1.0
Twist Right 4	7	-19	3.0	-8.1	0.2	1.4
Twist Right 5	10	-19	4.3	-8.1	0.4	1.4
Twist Right 6	13	-19	5.6	-8.1	0.6	1.4
Twist Left 1	-19	19	-8.1	8.1	1.4	1.4
Twist Left 2	-10	19	-4.3	8.1	0.4	1.4
Twist Left 3	-7	19	-3.0	8.1	0.2	1.4
Twist Left 4	-16	16	-6.9	6.9	1.0	1.0
Twist Left 5	-13	16	-5.6	6.9	0.6	1.0
Twist Left 6	-10	16	-4.3	6.9	0.4	1.0
Twist Left 7	-7	16	-3.0	6.9	0.2	1.0
Twist Left 8	-10	13	-4.3	5.6	0.4	0.6
Twist Left 9	-7	13	-3.0	5.6	0.2	0.6
Left 1	-19	4	-8.1	1.7	1.4	0.1
Left 2	-13	4	-5.6	1.7	0.6	0.1
Left 3	16	4	6.9	1.7	1.0	0.1
Right 1	-4	19	-1.7	8.1	0.1	1.4
Right 2	-4	13	-1.7	5.6	0.1	0.6

The results obtained here (Fig. 6-8) support and build on those presented in [12]. However, intuitive movement cues were induced by different STSs, thus indicating that the same STS on different finger pads felt differently. Then, to use the same hardware to transmit directional HG commands through the sense of touch, it would be feasible but only when using two sets of STSs (software selection) for the two grip styles.

Test 1 also revealed that exerting asymmetric STS can convey translational movement cues to move the user's hand left or right — adding a new DoF (left/right) with respect to those discovered in [12]. Interestingly, there was more consistency in these new movement cues with certain rotational directions for the index finger (rotational direction indicated in Figure 3), which is consistent with the greater sensitivity to distal stretches [54].

In fact, a positive rotational direction for the index finger tended to pull the fingertip thus keeping the entire finger aligned for small and large stimuli. This is due to the way our HF device effectively stretches the user's finger pad. The directional sensitivity [54] in effective stretching stimuli in one tactor direction does not affect the HG application because only the second quadrant in Figures 6-7 is enough for confidently transmitting this DoF. Additionally, there is a drawback to exerting tangential force or skin-stretch on *finger pads* under the principle of our HF device (Fig. 3-4). It supplies a second tactile stimulus in the opposite direction when the tactor returns to its central resting position. In essence, the device quickly moves the tactors to apply a STS (speed 21.6 mm/s), it holds the stimulus 3 seconds and then, the tactors slowly return to the central position (4 times slower: speed 5.4 mm/s).

In this regard, there were three qualitative remarks from participants: (1) after familiarization with the experiment, they understood that in case of doubt they could use the second stimulus (opposite to the first one) to confirm the direction of the induced movement cue; (2) the second stimulus was not perceived for certain STS; (3) the four participants who carried out both tactile tests agreed that Test 2 required more attentiveness to their feelings compared to the prior tests (Test 1a and 1b).

Due to findings of [38], we believe that participants only felt the second stimulus for STS involving large displacements because slow speeds reduced the stimulation salience. Moreover, who carried out Test 1 and 2 revealed that prior knowledge about a large number of possible HG movement cues increased the mental load. After completing Test 2, participants stated that they were not able to feel certain movement cues — which was consistent with the test because we only sent 4 movement cues but asked to report 8 + unsure feeling.

In its current design, the device enables us to address a broad user population (i.e. large variety of hand sizes), while being a low-cost, lightweight and portable HG device. However, during Test 1, we learned that proper sizing is very important for comfort and tactile sensation. So we had to reconsider the hand size classification of the participants by hand grip diameter, in order to set up the dimensions of the haptics device. After further research, we found that body posture modulates the perception of touch. For example, a recent study on the tactile sense of hands showed hand posture can dramatically impair the tactile sense of distance [53].

A different ergonomic issue emerged in Test 2 because we could not induce any backward movement cue with high salience. Only two STSs conveyed inconsistent guidance to move the hand back: (-7, -4) and (-4, -4) degrees. From the analysis of individual participant data, a few participants clearly perceived the backward movement cue with high salience. Recently, a similar device with a softer handle [14] succeeded in stimulating the backward movement cue to perform HG — future improvements in our hardware will thus include this feature.

In addition, more complex hardware designs as in [14] provide better control of the effective stretching action on users' finger pads. The tactors are displaced by two pantograph actuating 4 motors. This device allowed 4-DoF and only employed symmetric STS. Based on the findings of our study, we hypostatize that including asymmetric STS in this hardware could potentially: (1) add at least one additional DoF (moving laterally left/right); and (2) enhance the *cue salience* for all *movement cues* of at least 5-DoF.

Note about user finger slipping on tactor: slip barely happens in the device because 1) the textured rubber in contact with finger pad; and 2) the size adjustment to accommodate to different hand sizes. The user modulates his/her grasping force on the tactors to maintain slip-free contacts. For large angles of displacement, slip may occur at the end of the motion to avoid any unconformable finger pulling.

Limitations of our study include: (1) the lack of certainty about the existence of possible gender differences in perception, because the sample size in terms of volunteers was low for that; (2) the age of our participants was between 24-33 years old, because of the age of surgical residents. Thus, the effectivity of the HG device in older users must be investigated.

Additionally, future research should be focused on determining how to combine tangential skin displacement in a reliable manner with other haptic stimuli (multimodal stimulation), such as vibration, thermal, etc. Indeed, to induce *intuitive cues*, while accounting for perceptual interference during simultaneous stimulation [55], is an open question.

9 Conclusion

This research presents a novel and cost-effective way of communication between humans and machines. We have shown that tactile stimulation applied simultaneously to two of the user's fingers induced a high variety of *movement cues*, thus communicating how to reposition the user's hand in 3D space. This holds for two different finger pairs (thumb-index and the thumb-middle finger), which is promising for enhancing teleoperation applications such as robotic surgery.

Participants consistently interpreted "virtual pullings" and "virtual torques" on her/his hands, communicating movement information in 4-DoF (hand translations: forward/backward and left/right; and hand rotations: twist left/right and tilt up/down).

Our simple HG device exerts tangential force, or skin-stretch, on the user's *finger pads* with only 2 motors. The main contribution is the proof that translation and rotation *movement cues* can be interpreted by participants while using the same (but only difference in magnitude) circular motion of the tactors. Enabling a lightweight and affordable device, which is a key feature for the adoption of wearable haptic technology.

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