Shape Localization and Recognition using a Magnetorheological-fluid Haptic Display

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Abstract—Smart materials such as magnetorheological fluids (MRF) offer an interesting technology for use in haptic displays as changes in the magnetic field are rapid, reversible and controllable. These interfaces have been evaluated in a number of medical and surgical simulators where they can provide cues regarding the viscoelastic properties of tissues. The objective of the present set of experiments was first to determine whether a shape embedded in the MRF could be precisely localized and second whether ten shapes rendered in a MRF haptic display could be accurately identified. It was also of interest to determine how the information transfer associated with this type of haptic display compares to that achieved using other haptic channels of communication. The overall performance of participants at identifying the shapes rendered in the MRF was good with a mean score of 73% correct and an Information Transfer (IT) of 2.2 bits. Participants could also localize a rigid object in the display accurately. These findings indicate that this technology has potential for use in training manual palpation skills and in exploring haptic shape perception in dynamic environments.

Index Terms—Touch-based properties and capabilities of the human user; hardware and software that enable touch-based interactions with real, remote, and virtual environments; tactile communication

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1 INTRODUCTION

One application of haptic interfaces is in providing realistic physical interactions to users immersed in virtual environments. The need for these interfaces has been well documented in surgery, such as during the performance of minimally invasive procedures and when using surgical simulators for training. In these situations the absence of haptic feedback makes it difficult for the user to detect changes in the mechanical properties of tissues and to modulate effectively the forces exerted by a surgical instrument [1]. Haptic displays also offer promise in training medical practitioners in manual palpation during which changes in the composition of tissues, such as the presence of hard tumors in softer surrounding tissue, must be detected [2], [3].

Haptic interfaces use a range of actuator technologies including electromagnetic, piezo-electric, shape memory alloy and ultrasonic [4-6]. Electromagnetic and piezoelectric actuators are the most frequently used due to their small size, ease of control and relatively low cost. However, over the past five years there has been increased interest in creating programmable haptic effects on flat surfaces such as touch screens using either electro-vibration or ultrasonic vibrations. Both of these processes can be used to modulate the lateral forces induced by friction as the fingertip moves on the surface [6], [7], [8]. For medical simulators involving the interaction of a human operator with biological tissues, the challenge is to create realistic simulations of soft tissues that can vary in compliance. Haptic devices based on smart materials have the potential to overcome the bandwidth and dynamic range limitations of conventional electromagnetic actuators. Smart fluids, such as electrorheological fluids (ERFs) and magnetorheological fluids (MRFs), have been used to develop novel haptic devices [9], [10], [11]. These fluids exhibit a substantial change in their rheological behavior when an external electric or magnetic field is applied [12]. MRFs appear more suitable for haptic displays than ERFs due to their good yield stress range, response time and simplicity of their excitation system. ERFs require driving voltages up to 10 kV, which are two orders of magnitude higher than those used for MRFs.

MRFs are a suspension of micrometer-sized ferrous particles in a nonconductive carrier fluid such as silicone oil. When the fluid is subjected to an externally applied magnetic field the particles form columns and align themselves in the direction of the flux lines of the applied field. The columns act to resist shearing or the flow of the fluid. The intensity of the applied magnetic field determines the apparent yield stress of the fluid. When the magnetic field is removed the fluid rapidly returns to its liquid state. These features make MRFs a technology that is rapid, reversible and controllable. The amount of torque/force that an MRF actuator transmits is controlled by varying the magnitude of the applied field. MRFs exhibit such behavior in three modes of operation, namely shear, flow, and squeeze [12]. In the shear and squeeze modes, the fluid resists the motion of the plates perpendicular to or along the applied field, respectively; in the flow mode, the flow of the fluid itself is resisted due to the particle columns formed. The shear mode has been used to create MRF-based clutches and brakes as part of haptic interfaces [10], [11], whereas the squeeze mode has been used to develop haptic displays that can present compliance cues to the hand [13], [14].

Virtual objects of varying shape and size have been created using haptic displays based on MRFs. These have been explored manually using either a gloved hand or through a

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membrane enclosing the MRF [12], [15], [16]. By changing the intensity of the magnetic field it is possible to create the perception that one is manipulating different shapes with varying stiffness. These features have led to an interest in using MRF displays to simulate the viscoelastic properties of tissues and tumors in medical applications such as presenting forces associated with cutting tissue [17], [18] or identifying the location of tumors in soft tissue [19], [20].

Many existing haptic devices used to generate force and tactile feedback utilize classical electromagnetic actuator technology. These have been successfully employed in force-driven virtual instruments for simulating minimally invasive surgical procedures [21]. Development of devices based on MRFs requires a close interplay between implementing the actuator technology and evaluating its efficacy in controlled psychophysical studies [22]. Such displays may be very effective at presenting specific types of haptic cues and at the same time may be used to elucidate some fundamental properties of human haptic perception.

The objective of the present experiments was to determine whether shapes presented in a MRF haptic display could be accurately localized and identified through manual exploration. It was also of interest to determine how the information transfer associated with this type of display compares to that achieved using other haptic devices [23].

2 EXPERIMENT ONE

The first experiment examined the accuracy with which participants could localize the position of a shape in the MRF. This provided a baseline measurement in terms of human spatial processing given the properties of the MRF display.

2.1 Participants

Fifteen normal healthy individuals, 7 males and 8 females ranging in age from 20 to 25 years old participated in the experiment. The participants had no known abnormalities of the skin or peripheral sensory or vascular systems. The experiment was conducted according to the ethical guidelines of the Declaration of Helsinki.

2.2 Apparatus

The haptic display is composed of 16 solenoids (see Fig. 1) configured in a four-by four array and positioned below a plexiglass chamber with a base of 200 mm x 200 mm, containing the MRF. The center-to-center distance between the solenoids is 45 mm. Each solenoid is composed of 305 turns of enameled copper wire, arranged around a cylindrical ferromagnetic core with a diameter of 21 mm. The core size was chosen based on a trade-off between accessibility for subjects to the MRF and the magnetic saturation of the iron. The MR fluid used in the display is MRF-140CG (Lord Corporation, Cary NC, USA) with a viscosity of 0.280 Pa.s (at 40° C) and a density of 3.54-3.74 g/cm^3.

The 16 coils are powered by four 12 V, 75 Ah batteries. The control system and power electronics consists of 16 Pololu drivers (18 V, 25 A) and an Arduino Mega microcontroller board, connected to a PC via USB. Matlab code was used to control the current in the coils which resulted in the generation of shapes in the MR fluid. The perimeters of the shapes were not precisely defined, but the profile of the magnetic flux density permitted the shapes to be rendered with smooth edges.

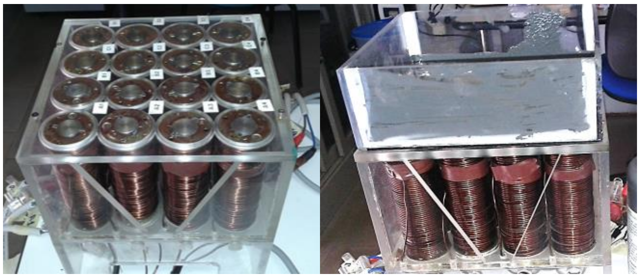

Figure 1. Four-by-four array of solenoids (left) and mounted beneath the MRF in the plexiglass chamber (right)

The spatial resolution of the display is related to the size of the excitation system which was estimated using FEM. Numerical simulations showed that the spatial resolution on the base of the display is approximately 20 mm, consistent with the diameter of each of the 16 ferromagnetic cores which comprise the excitation system. To investigate the behavior of the magnetic field inside the MRF when one or more coils are activated, several simulations were performed using FEM. Fig. 2 shows the map of the shear stress in the MRF in two different configurations: (a) when only one coil excites the fluid; and (b) when two neighboring coils, oppositely fed, excite the fluid. The profiles of the shear stress as a function of the distance along the lines passing through the centers of the ferromagnetic cores are also shown. The interference between adjacent MRF elements is similar to that reported previously [16], [20].

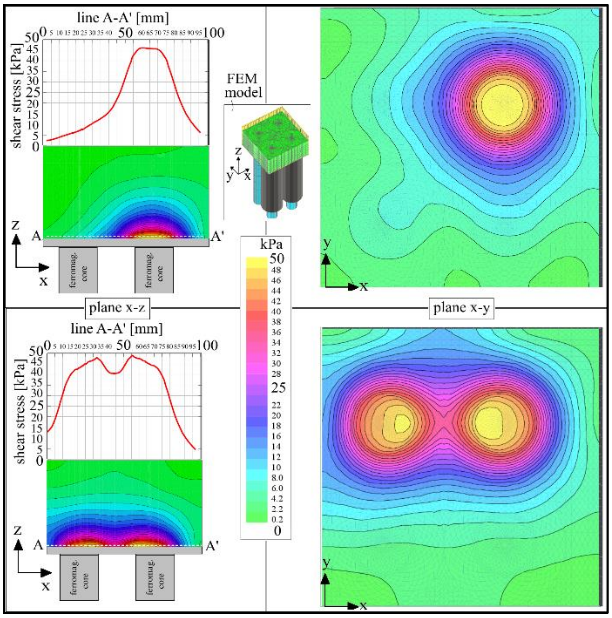

Figure 2. Shear stress in the MRF when ony one coil excites the fluid (upper plot) and when two neighboring coils oppositely fed excite the fluid (lower plot).

The stiffness of the display was estimated by applying stepwise strains to the MRF as the magnetic field was increased. The stiffness varied from 0.14 N/mm at 0 T to about

1.4 N/mm at 0.5 T., and saturated as the magnetic flux density increased, due to the known nonlinear behavior of the shear stress/B field curve. Since the magnetic flux density is not uniform along the height of the MRF column, the stiffness changes as a function of height. Assuming a maximum value at the base of the display, at a height of about 20 mm the stiffness is reduced by 85-87%.

2.3. Procedure

Participants sat directly facing the MRF haptic display that was obscured from view by a cardboard enclosure. A glove was placed on their preferred hand which was then inserted through a hole in the enclosure to make contact with the MRF display. Participants were initially familiarized with the display by manually exploring it as different coil positions were activated.

On each trial during the experiment one of the 16 solenoids was activated creating a rigid column in the MRF. Participants were instructed to localize the shape in the MRF and indicate its position using a visual template positioned in front of them. The template was a four-by-four grid with each of the 16 positions labelled by letter and number (A1, A2 etc), with A being the column to the right of the participant and D the column to the left. The row marked 1 was closest to the participant's hand when it was inserted into the display. Participants verbally indicated where the shape was felt and their responses were recorded. Each position was presented four times in a random order giving a total of 64 trials per participant.

Participants were not given any instructions as to how they should explore the MRF in order to localize the shape. They generally moved their hands in the MRF so as to identify the grid coordinate where the shape was formed. Participants used either the whole hand or one or two fingers to explore the fluid. No time limit was imposed to perform the task and participants typically responded within 12 s.

2.4 Results

The accuracy with which participants identified the location of the shape in the array varied with position, from a low of 68% correct to a high of 98% correct as shown in Table 1. The overall group mean was 86% correct. A repeated-measures one-way ANOVA performed on these data revealed a significant effect of location ($F(15,210)=4.94$, $p<0.0001$) and a significant effect of row ($F(3,42)=8.43$, $p<0.0001$). Post hoc analyses revealed that localizing stimuli along the third row (A3-D3) was significantly more difficult than on any of the other rows. These findings indicate that the display had adequate spatial resolution to present stimuli that were perceived to be in distinct locations.

The stimulus-response confusion matrix indicated that most errors involved mislocaliztion by a single position. The information transfer (IT) calculated from this matrix measures the increase in information about the signal transmitted from knowledge of the signal received. It is calculated from the conditional and joint probabilities of the stimulus-response pair, the a priori probability of the stimulus and the probability of the response [23]. The mean IT was 3.23 bits which indicates that for this task and set of stimuli between 9 and 10 locations can be identified.

TABLE 1.

Group mean percent correct responses at each location in the array. The first row (A1-D1) was closest to the participant with the column marked A to the right and D to the left.

D4	98%	**C4**	73%	**B4**	87%	**A4**	83%
D3	68%	**C3**	75%	**B3**	90%	**A3**	83%
D2	87%	**C2**	70%	**B2**	90%	**A2**	92%
D1	88%	**C1**	90%	**B1**	98%	**A1**	97%

3 EXPERIMENT TWO

The first experiment demonstrated that shapes presented in the display can be localized haptically. The second experiment was an absolute identification study in which participants had to identify which of ten shapes generated in the MRF display was presented. The shapes were designed so that there were incremental changes in their linear dimensions (shapes 1 and 2, or 8 and 9) or orientation (shapes 4 and 8, shapes 5 and 9) so that it would be possible to determine how dimensional changes influenced perception (see Fig. 3). The dimensions of the shapes specified in Fig. 3 take into account that the center-to-center distance between two neighboring ferromagnetic cores is about 45 mm.

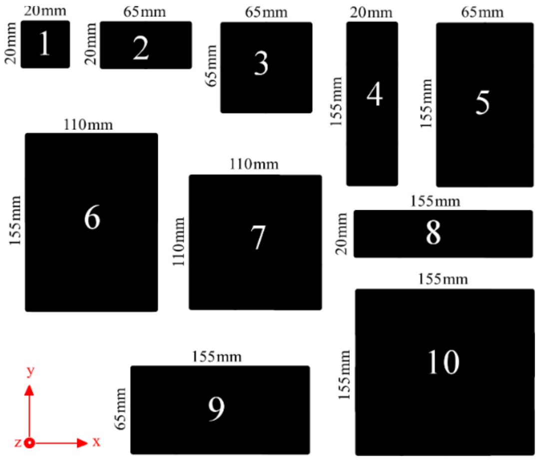

Figure 3. Template of numbered shapes presented in the MRF display with the main dimensions specified. All shapes are approximately 10 mm along the z-direction.

3.1 Participants

Fifteen normal healthy individuals, 7 males and 8 females ranging in age from 20 to 26 years old participated in the experiment. They had no known abnormalities of the skin or peripheral sensory or vascular systems. They had not participated in the first experiment. They gave their informed consent and the experiment was conducted according to the ethical guidelines of the Declaration of Helsinki.

3.2 Apparatus and Procedure

The MRF display used in the first experiment was used in this study. Participants were initially familiarized with the display by manually exploring it as different shapes were generated by activating the coils. On each trial one of ten shapes (see Fig. 3) was generated and participants were required to identify the shape verbally using a visual template (similar to Fig. 3). Each of the shapes was presented randomly ten times giving a total of 100 trials. Responses were recorded by the experimenter. There was no time limit imposed on participants to make their responses and they typically responded within 30 s. After each response the hand was lifted out of the MRF but kept within the enclosure housing the display. A rest break was provided when requested. No feedback was given regarding the responses during the experiment.

3.3 Results

Participants were not given any explicit instructions as to how they should explore the MRF in order to identify the shapes. They generally moved their hands in the MRF so as to follow the contour of the shape presented. This was performed using either the whole hand or one or two fingers that traced the perimeter of the shape (see Fig. 4). This exploratory procedure in which the small-scale features of a shape are extracted is known as contour following [24].

Figure 4. Method of exploration: multiple fingers (left) one finger (right)

The participants' responses were initially analyzed in terms of the percentage of correct responses for each shape presented. Across participants the mean scores ranged from 65% to 85%, with an overall mean score of 73% correct. The group data are illustrated in Fig. 5. A repeated-measures ANOVA performed on these data revealed a main effect of shape (F(9,126)=16.12, $p<0.001$). Post-hoc analyses indicated that the most distinctive shapes were 8, 9 and 10, each of which was identified significantly more often than the other shapes. There does not appear to be any relation between the size of the shape and the ability to identify it, other than when the shape encompassed almost the whole display surface it was one of the easiest to identify.

The confusion matrix of the participants' responses shown in Table 2 indicates which stimuli were most frequently confused. In general, the most common errors for any shape involved identifying a shape that was geometrically similar to the target shape (e.g. patterns 1 and 2, 4 and 5). Errors involved misperceiving the linear extent in both the horizontal and vertical directions.

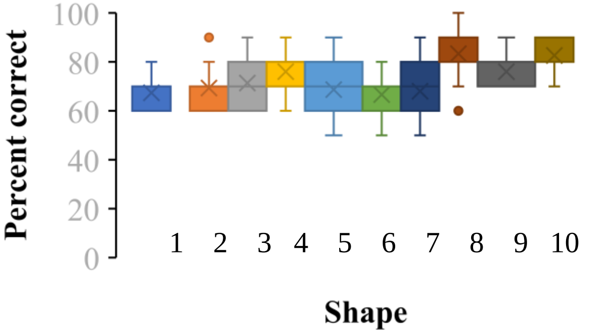

Figure 5. Box and whisker plot of the group data for each shape presented.

The IT was calculated from the confusion matrix of the pooled data (Table 2) using the relevant equations in Tan et al. [23]. IT is usually preferred to percent-correct scores as the performance measure in identification tasks. In this study, the IT calculated from the group data was 2.20 bits. The calculation 2^{IT} is interpreted as indicating the maximum number of stimuli that can be correctly identifed. For this set of ten stimuli between four and five shapes can be reliably identified.

TABLE 2.

Confusion matrix of the group responses with scores out of the total of 150 trials for each stimulus (St). The highlighted diagonal represents correct responses.

Participants' Responses

St	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	101	44	5	0	0	0	0	0	0	0
2	24	104	19	0	0	0	0	3	0	0
3	1	32	106	0	0	0	11	0	0	0
4	0	0	0	114	36	0	0	0	0	0
5	0	0	0	31	103	16	0	0	0	0
6	0	0	0	2	15	100	7	0	0	26
7	0	0	14	0	0	16	102	0	5	13
8	0	22	1	0	0	0	0	125	2	0
9	0	0	3	0	0	0	27	6	114	0
10	0	0	0	0	1	20	6	0	0	123

4 GENERAL DISCUSSION

These two experiments were focused on evaluating the effectiveness of the MRF display in presenting shapes that are localized or identified haptically. The results from the first experiment indicated that participants could accurately localize a site in the display with few errors. Their performance on this task (86%) is superior to that reported when people localize the site of stimulation on the body (59% correct) with a 16-element tactile display [25]. This finding is promising in terms of using this type of haptic display to render shapes for training purposes that involve finding a target region such as a tumor in more compliant tissue. In the second experiment participants determined the two-dimensional shape presented in the MRF display by tracing its outline. This exploratory procedure (EP) known as contour following reveals the small-scale features of a shape which were important in the experiment to distinguish between shapes that differed only with respect to the length of a single edge (e.g. 2 and 3 in Fig. 3). Previous research on the relative efficiency of different EPs has shown that contour following is both necessary and sufficient for extracting information about the precise shape of an object [26]. In the absence of any instructions, it is the EP that people naturally use when asked to make a judgment about the exact shape of an object. Contour following is relatively slow (8-16 s) and requires successive sampling of an object's contour over time [27]. The time taken to identify the shapes in the MRF display is similar to that reported in other studies of haptic shape recognition [26], [28]. Less precise information about shape can be extracted by molding the fingers to the object's contours, a procedure known as enclosure which can be performed rapidly (1-4 s). This EP was rarely observed in the present experiment.

In order to perceive the shape in the MRF display proprioceptive cues from the moving hand and digits would have been integrated with cutaneous cues related to sustained pressure and lateral skin stretch. The tactile signals would provide information about the relative velocity between the finger and the surface and if the tactile velocity information was integrated over time these cutaneous signals would provide an estimate of the relative displacement between the hand and the shape rendered in the MRF. The processing of these haptic cues relies on the integration of information that is changing both spatially and temporally. Much of the research on shape perception has focused on the perception of curvature, where it has been found that the overall curvature of a shape has a direct influence on the ability to identify it [29]. Identification of the shapes in the present experiment primarily relied on perceiving the relative lengths and orientations of the elements making up the shape and so proprioceptive cues related to the linear extent of finger and hand movements would have been essential to performance. The haptic perception of space is known to be anisotropic in that the perception of linear extent depends on the spatial orientation and location of the shape being explored [30] [31]. However, in the present study both radial and tangential movements were required to explore the shapes and so the overestimation of radial movements that has been frequently reported when judging linear extent [30] should not have been a major factor in determining the contour of the shape.

The overall performance of 73% correct in the second experiment is good but indicates that the resolution of the display will need to be improved if it is to be used to present realistic topologies of tissue in a simulator. The spatial resolution of the MRF haptic display is around 20 mm and the contours rendered by the magnetic field are not sharp and so edges are not distinct. The spatial resolution of the display can be improved by reducing the cross-section of the ferromagnetic cores and increasing the number of cores. Then, by using mobile pistons to focus the flux in a specific region of the MRF, it is possible to modify both the spatial resolution and the magnetic field [12]. This can be accomplished by controlling the distance between the pistons and the base of the display and by tuning the current in the coils.

A further improvement to the device that may enhance its usefulness in displaying shape is to modulate the stiffness of the display. This could be achieved by controlling the applied magnetic field locally. It has been shown that with haptically rendered shapes, size identification in simulated environments is inferior to that achieved in real environments when the stiffness of the virtual surfaces is limited [32]. Tactile elements based on encapsulated MRF have recently been developed which can change in stiffness across the range required to mimic the properties of normal tissue and tumors [20]. Young's moduli between 400-500 kPa have been achieved for these elements with magnetic flux densities around 200-300 mT.

For many perceptual dimensions the ability to identify a particular stimulus in isolation is limited and stands in marked contrast to the human capacity to discriminate between pairs of stimuli. In his classic paper on the human capacity for processing information, Miller [33] noted that with stimuli that vary along a single dimension (e.g. the pitch of a tone) the transmitted information is limited to 2.3 to 3.2 bits which is equivalent to 5-7 perfectly identifiable levels. In haptics research it has usually been found that the unidimensional channel capacity, such as perceiving the shape of an object, is lower than these estimates which were primarily derived from visual and auditory stimuli. Cholewiak et al. [34] reported that for both force and stiffness only two to three levels can be reliably identified. Similarly, haptic perception of geometric features of a virtual object such as its size has been shown to be limited with only three to four sphere sizes being identified [35]. The four to five shapes consistently identified in the present study is comparable to the performance reported for these other dimensions perceived haptically.

One of the many applications of haptics in medicine is in training individuals to detect changes in tissue properties such as those associated with tumors. In soft tissues such as the breast or lung, tumorous tissue can be two to three times stiffer (Young's modulus of 400-500 kPa) than the surrounding tissue. With minimally invasive surgery the tactile cues from the tissue are absent and lump localization becomes challenging [2], [3]. A MRF-based haptic display offers the opportunity for training individuals in manual palpation for the detection of tissue anomalies. For this purpose, it has been estimated that the display should be capable of rendering stiffness between 200 and 600 kPa with a spatial resolution of less than 5 mm [36]. Such performance has been achieved by devices that create localized magnetic fields by controlling the position of small permanent magnets [20], [37].

In the context of using MRF haptic displays to simulate tissue properties for training health care professionals, the present findings indicate that both the location and shape of an object can be rendered in a MRF display. There are clearly limitations with respect to the nature of the contours that can be displayed due to the properties of the magnetic fields. However, the dynamic behavior of the MRF could be exploited by developing displays that can move shapes along a given trajectory in the fluid or change the profile of the shape surface dynamically.

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