Comparing the Role of Lateral Force During Active and Passive Touch: Lateral Force and its Correlates are Inherently Ambiguous Cues for Shape Perception under Passive Touch Conditions

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Abstract

Lateral forces are important cues for shape perception through active touch [1,2]. They can elicit illusory haptic shapes, or perceptually transform the shape of physical objects [1]. Here, it is shown that lateral force, and correlates such as acceleration and velocity, are inherently ambiguous as shape cues under passive touch conditions. The lateral forces arising when passively touching objects with different shapes can be equal. Lateral force ambiguity can also happen during active touch, when an object moves relative to a subject's limb. Lateral force ambiguity may be used to explore two important, unsolved questions: whether active and passive touch percepts are equivalent [4], and whether they arise from the same brain mechanisms [4]. A method is proposed, and used, to generate geometryless, force-matched stimuli to compare the role of lateral force during active and passive touch, while minimizing other cues. Such comparisons have been extremely hard to make because of the difficulty to meaningfully match the many factors involved [4-8].

1. Introduction.

Lateral forces (LFs) are experienced when a virtual or physical surface is actively or passively touched [1-3]. For low horizontal accelerations, LFs depend on the local slope of a surface and on the normal force that is applied during surface exploration [1,2]. LFs are perpendicular to this normal force. Figure 1 shows the magnitude of two different LF fields (LFFs). Here, the direction of the LFs is parallel to the horizontal axis (Fig. 1a,b, top panels, lateral force direction). One LFF (Fig. 1a, bottom panel) corresponds to a Gaussian-shaped, virtual or physical bump [1,2] (Fig. 1a, top panel). The other (Fig. 1b, bottom panel) corresponds to a Gaussian-shaped virtual or physical hole [1,2] (Fig. 1b, top panel). These LFFs are

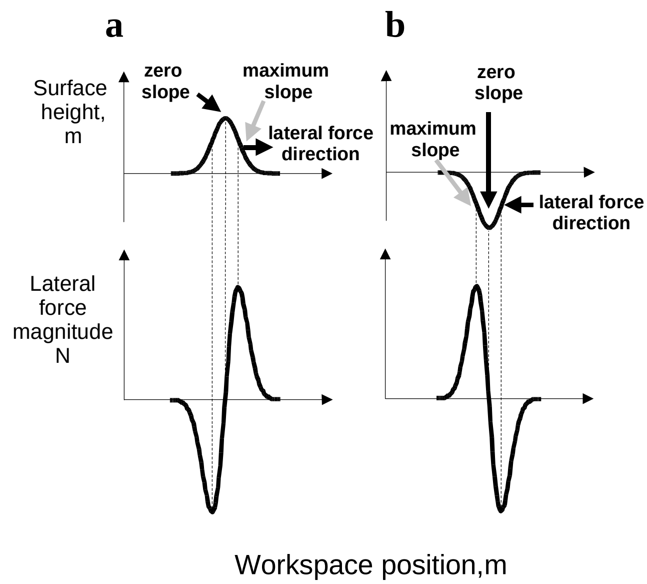

Figure 1. The lateral force fields that are experienced when touching a physical or virtual bump (a) or hole (b). By convention, the magnitude of the forces (bottom panels) is positive when the direction of the force is from left to right (a, top panel). The lateral forces depend on the local slope of the shapes and on applied normal force (parallel to the vertical axis, not shown). Given the same vertical force, when a shape has maximum slope (in absolute value, top panels), the magnitude of the LFs is maximal (in absolute value, bottom panels). When the virtual or physical shapes (top panels) have zero slope, there is zero lateral force (bottom panels).

shown here in arbitrary, fixed positions in a workspace. For low horizontal accelerations, the same LFFs are experienced by a subject when touching the surfaces either actively or passively.

This paper proposes that LF is an ambiguous cue for shape perception under passive touch conditions. The reasons for this ambiguity are presented. They are discussed with some detail because, to the best of my knowledge, LF ambiguity has not been presented in the literature before. Finally, a method is proposed to experimentally explore the perceptual consequences of this ambiguity and to compare the role of lateral force during active and passive touch.

In what follows, it will be assumed that a subject experiences an LFF through a haptic manipulandum such as the one described in [1], although LFs are also present, together with other cues, when touching a surface directly, for example, through a fingertip [9].

2. The ambiguity of lateral force as a cue for shape perception.

Let us assume that a subject holds the haptic manipulandum static at the horizontal location P (Fig. 2, bottom panels), and passively touches a virtual or physical surface that moves along the horizontal axis. On the basis of LF alone, with no available information about the movement of the surface, how could the subject decide whether the surface was a bump (Fig. 2, top panels, grey curves) that moved from left to right, or a hole (Fig. 2, top panels, black curves) that moved from right to left at the same speed? In either case, the forces at P are equal (Fig. 2, bottom panels). Note how the LFFs associated to the hole and the bump are mirror images of each other (Fig. 2, bottom panels, grey and black curves). They are symmetrical with respect to the vertical axis that crosses through P.

This symmetry is central to LF ambiguity. Without loss of generality, let us assume that the subject holds the manipulandum static at P=0 m. Given the workspace position x and the vertical force F_v, for every LFF $F_1(x,F_v)$ that is not symmetrical with respect to any vertical axis, there is always a different force field, $F_2(x,F_v)$, such that $F_2(x,F_v)=F_1(-x,F_v)$. F_1 and F_2 are mirror images of each other (i.e., symmetrical with respect to the vertical axis at P=0 m). F_1 and F_2 correspond to different shapes. LFs associated to bumps in F_1 correspond to forces associated to holes in F_2, as happens for the LFFs shown in Fig. 2. The equivalent case happens to forces associated with holes in F_1, which correspond to bumps in F_2.

In general, let $F_1(x-x_0(t),F_v)$ be an arbitrary LFF that moves across the workspace. Its position changes over time, following an arbitrary function $x_0(t)$. A mirror LFF, F_2, can always be constructed:

$$F_2(-x+x_0(t),F_v)=F_1(-x+x_0(t),F_v)$$

The mirror LFF $F_2(-x+x_0(t),F_v)$ moves in exactly the opposite way as $F_1(x-x_0(t),F_v)$ does. Given the symmetry of the LFFs, this implies that the forces from either field are equal at P=0m. Other cases of ambiguous LFFs could

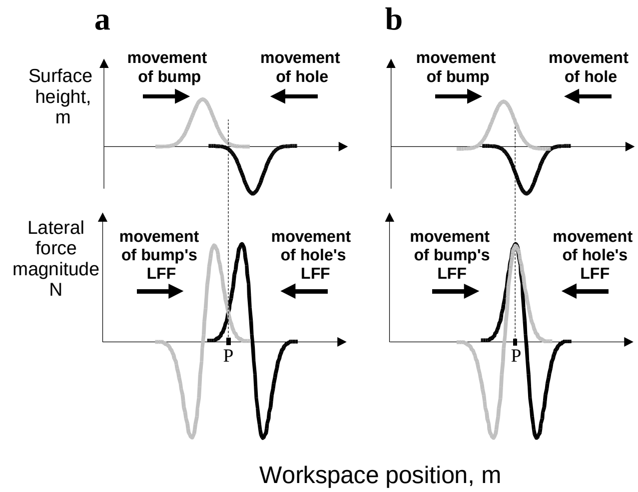

Figure 2. The ambiguity of lateral force during passive touch. A subject holds a haptic manipulandum static at P (a,b, bottom panels). When a physical or virtual bump (a,b, top panels grey curves) or hole (a,b, top panels, black curves) move, their corresponding force fields (a,b, bottom panels, grey curves for a bump's field, black curves for a hole's field) also move. If a physical or virtual bump moves from left to right (a, gray curves), the lateral forces at P are equal to those experienced from a physical or virtual hole (a, black curves) that moves in the opposite direction (from right to left) with the same speed. As the movement of the fields continues in this way over time (b), the lateral forces at P from either the bump's or the hole's fields are equal.

also be found. For example, the forces arising from passively touching a moving LFF, F_3, could also be obtained from a different LFF that moved faster than F_3, but had slower-varying forces with respect to workspace position. The increase in velocity can be compensated for by a slower force variation.

LF is related to the acceleration in the horizontal axis through Newton's Second Law. Given the shape ambiguity of LF, any acceleration caused by LFs in the horizontal axis is also ambiguous: the same acceleration could be caused by LFs originating from two or more different virtual/physical shapes. By integrating acceleration, the LF-related velocity in the horizontal axis is obtained. As acceleration is ambiguous about shape, so are its integrals, including position. This also happens for the derivatives of acceleration (jerk) and force. Intuitively, given that LF is ambiguous, a given pattern of force variation can be obtained from different shapes/LFFs.

What happens during active touch? More information is available in addition to LF. For example, a subject can

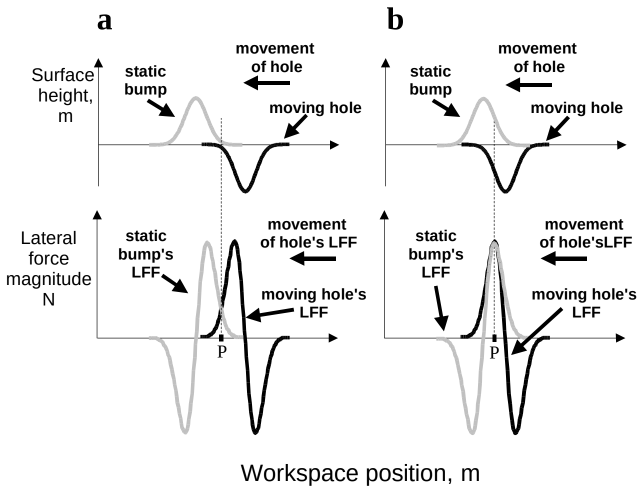

Figure 3. The ambiguity of lateral force during active touch. A subject explores a static, physical or virtual bump (a, top panel, grey curve) by moving a manipulandum from right to left. The point of contact manipulandum/surface is at P, so the corresponding lateral forces are experienced there (a, bottom panel). The same lateral forces (a, bottom panel, black curve) can be experienced also from a physical or virtual hole (a, top panel, black curve) that moves from right to left at an adequate rate relative to the manipulandum. This continues (b) for as long as the moving hole tracks the subject's movement.

track past hand movements, the relationship between workspace location and lateral force, or whether an object is static or not. A subject can generate expectations from this information and use them to guide future hand movements, too. However, LF ambiguity may also arise during active touch. For example, let us consider a subject that actively explores a virtual or physical bump that is statically positioned on the workspace (Fig. 3a,b, grey curves, top panels). The subject explores it by moving the haptic manipulandum from right to left. The horizontal position of the manipulandum as the surface is explored is P. Let us consider what would happen if, instead of touching the static bump, the subject touched a virtual or physical hole that also moved from right to left. If this hole moved at an adequate rate relative to P (Fig. 3a,b, black curves, top panels), then the LFs experienced by the subject when touching either the static bump or the hole that moves are equal. Such an ambiguous "differential touch" (because the object moves relative to the subject's hand) situation seems unlikely, but may happen, for example, when exploring/grasping a moving object. Subject performance in a differential touch situation is also potentially important for the rendering [10] of dynamic, virtual haptic objects.

3. Experimentally comparing the perceptual role of lateral force during active and passive touch.

There are several difficulties to experimentally explore the perceptual consequences of LF ambiguity. When actively or passively touching a natural, physical shape, object geometry may help resolve the ambiguity. To explore LF ambiguity under passive touch conditions, it is also necessary to have a method to construct stimuli that have meaningful force levels and rates of variation. The presentation time of the stimuli must be meaningfully controlled, too.

A within-subject setup, consisting of three experimental tasks, was designed to deal with these difficulties and used to explore the effect of lateral force ambiguity during active and passive touch.

In Task 1, human subjects actively explored and classified geometryless, LF-based Gaussian virtual surfaces [1,2] into shape categories ("bumps", "holes"). These stimuli were geometryless because they reproduced the LFs encountered when exploring a physical shape, but they did not vertically move a subject's limb as the geometry of a physical shape would do. To achieve this, the apparatus described in [1] was used. This apparatus consisted of a haptic interface (PenCat/Pro, Immersion Canada Inc.) that was connected to a manipulandum. The manipulandum rolled on top of a flat physical surface. A subject used her index finger to roll the manipulandum horizontally and sideways. Simultaneously, the haptic interface rendered the virtual surfaces. The subject's exploratory movements [11] (in this case corresponding to the haptic manipulandum's movement on the workspace) were recorded in each experimental trial, together with the lateral forces experienced by the subject (which defined the virtual shapes), as well as the vertical force applied by subjects to hold the manipulandum onto the flat physical surface. These vertical forces were used to compute the LFs [1]. All this information was recorded at 1kHz. The virtual shapes were designed to be easily perceived when actively explored (k=0.5cm, w=2cm [1]). Forty virtual bumps and forty virtual holes were used as stimuli in this task.

In Task 2, the same apparatus was used. The information that was recorded during Task 1 was played-back to subjects, but under passive-touch conditions. This was equivalent to passively experiencing virtual surfaces that moved. Note that the "movement" of these virtual surfaces corresponded to the exploratory movements used by subjects when actively exploring the surfaces in Task 1. The order of presentation of the played-back trials was randomly changed. The subjects were asked to maintain the manipulandum static into a given position. Subjects were told that a computer-generated surface would move underneath the manipulandum. Subjects were asked to classify these surfaces into the same shape categories used in Task 1. The subjects were not told that his/her previous performance data were being played-back to them. During Task 2, the subjects' hand and index finger were not immobilized, and small movements caused by the LFs were present. This was a necessary compromise, because immobilizing the subject's finger/hand would introduce more forces into the experiment, thus affecting the experimental LFs. Given the shape ambiguity of LF-related horizontal position changes (see Section 2), these displacements were not shape cues.

Two playback modalities were tested. In Playback I trials, the lateral forces presented were exactly the same as those recorded during Task 1. The vertical forces applied by subjects during Playback I trials were not used to compute the lateral forces. All the trials recorded during Task 1 were used as Playback I trials.

Haptic memory of Task 1's performance and stimuli was a possible influence on subjects' performance during playback. Among several possibilities, LF or the relationship between LF and the vertical forces applied by subjects, could be memorized and used to classify surfaces during playback. Playback I trials should shed light on the first possibility. Playback II trials were designed to explore the second possibility. In these trials, the current vertical forces exerted by subjects were used to compute the LFs. This reproduces the lateral/vertical force relationship that is present when touching natural, physical shapes [1]. Note that the LFs were not the same as those presented during Task 1 or Playback I trials. All the trials recorded during Task 1 were also used as Playback II trials.

Task 3, a repetition of Task 1 with new stimuli, was applied after Task 2. It was designed to rule out fatigue as the cause of subject performance during Task 2. In all tasks, the probability of classifying a stimulus into a shape category was used to measure performance [1,2]. All tasks were given in a single session, and were separated by short breaks. Subjects had frequent rest breaks throughout the experiment.

4. Results.

Four right-handed subjects, ages 27-44, participated in the experiments. They gave informed consent, were naive to the purpose of the experiments, did not have calluses on their right index finger, nor report any hand injury/disease. Two subjects were female and two were male.

In Task 1, subjects easily classified the virtual bumps (Figure 4, left panel, Task 1, Active exploration) and holes (Figure 4, right panel, Task 1, Active exploration). However, when Passive Playback I trials were presented, a dramatic decline in performance was observed (Figure 4, both panels, Passive playback I, results from the same subject are plotted with the same symbol). The lateral forces were exactly the same in Task 1 and during Passive Playback I trials; their duration, magnitude and rate of force variation were equal. This indicates that, while LFs determined shape classification performance during active

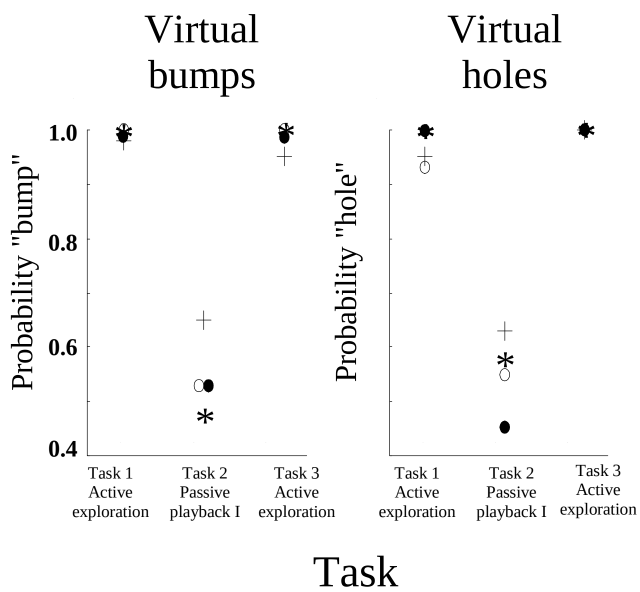

Figure 4. Subjects could not classify geometryless, lateral-force-based virtual surfaces when passively touching them. Different symbols denote data from different subjects. When subjects actively explored the virtual surfaces, they easily classified them (Task 1, both panels). However, when the same lateral forces (i.e., virtual surfaces) were passively played back to them, subjects could not reliably classify them into shape categories (Task 2, Passive playback I, both panels). This happened for both the virtual bumps (left panel) and holes (right panel). During Task 2's Passive Playback I trials, the lateral forces were independent from the vertical forces applied by subjects to hold the manipulandum down. Subjects' performance decline was not caused by fatigue. When actively exploring virtual surfaces again, the excellent performance of Task 1 was repeated (Task 3, both panels).

touch, the same LFs were not useful to perform the same classification task during passive touch. A similar decline in performance was found for Playback II trials (Figure 5, both panels). The decline in performance in both passive conditions was not due to subject fatigue. In Task 3, when subjects actively explored and classified new stimuli, their excellent performance returned (Figures 4 and 5, both panels, Task 3, Active Exploration).

5. Discussion and future work.

The methodology presented here allows to compare the role of lateral force during active and passive touch and the perceptual consequences of LF ambiguity. More

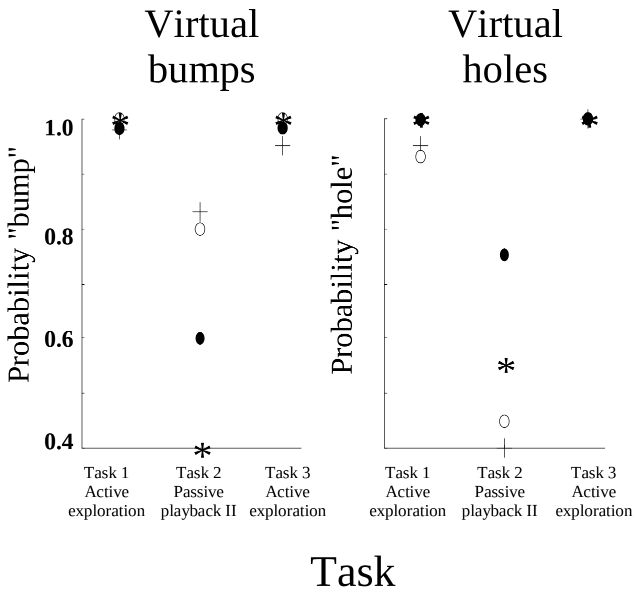

Figure 5. Subjects' virtual shape classification performance also declined when passively-experienced lateral forces depended on the vertical force applied to hold the manipulandum down (Task 2, Passive playback II, both panels). In contrast, subjects easily classified the lateral forces into shape categories when actively touching them (Task 1, both panels). Subjects' performance decline was not caused by fatigue. When actively exploring a new set of virtual surfaces (Task 3, both panels), the excellent performance of Task 1 was repeated. Different symbols denote data from different subjects.

generally, by using force and geometry decorrelation [1], illusory (virtual [1]), stimuli can be generated and used to explore the perceptual/motor consequences of LF ambiguity during active, passive and differential (active exploration of moving objects) touch. The LFs applied to subjects through a haptic interface when actively exploring illusory, physical or hybrid shapes (which combine physical and virtual shapes [1]), can be recorded and passively played back to subjects through the same interface in many different manners. This provides a way to construct perceptually relevant, LF-matched stimuli, with or without geometrical cues, and to use them to compare subject performance in the active and passive cases. Such comparisons have been extremely hard to make because of the many factors involved, and by the difficulty to match them during active and passive conditions [4-8]. In contrast, by using LF-matched virtual surfaces under passive touch conditions, it is possible to eliminate object geometry and minimize the effect of important touch information (force/space relationships, past limb movements, information about object movement, cognitive factors such as expectations, etc.) that is available during active exploration. This approach may be used alone or in combination with neurophysiological and brain imaging techniques to explore whether active and passive touch rely on the same brain mechanisms. LF ambiguity can be extended from the one-dimensional LFF case discussed here to the two-dimensional one, which involves more spatially sophisticated LFFs that can move in two or three-dimensional trajectories.

It is known that active touch can be superior to passive touch when the exploration times are comparable, and that passive touch may be as good as active touch when allowing for longer passive exploration times [6]. In the experiments reported here, the exploration time was the same in both the active and passive cases. However, there are many differences between the experimental conditions of [6] and the current experiments. This makes a direct comparison very difficult. Here, cutaneous information was minimized, because subjects explored the surfaces through a manipulandum. Also, object geometry was eliminated, and the forces used in the stimuli were matched. Given these considerations and, more importantly, the inherent ambiguity of LF, the decline in subject's classification performance during passive playback can be attributed to LF ambiguity and to the diminished role of cognitive factors that are present during active exploration.

The ambiguity of LF suggests that the neural processing mechanisms used by subjects to determine shape in both active and passive conditions do not rely only on force cues. For example, during active touch, object geometry is not always necessary to determine shape perception [1]. During passive touch, object geometry may help resolve LF ambiguity (i.e., a subject's finger moves up and down following the geometry). It is possible, however, that highly stereotyped sequences of LFs could be used or learned to perceive the shape of an object during passive presentation of LF alone. Of course, when passively touching a surface directly, and not through a tool or haptic manipulandum, many other shape cues are available [9].

Given the many different ways in which an LFF can be interpreted due to LF ambiguity, the experimental approach presented here may help reveal the assumptions that the nervous system would make when processing LF in passive and active situations. For example, in the current experiments, subject classification performance declined in all the passive conditions, compared to the high performance in the active cases. However, performance in Passive Playback II trials was well above chance for several subjects. Given that force is inherently ambiguous when presented passively, this suggests that the observed above-chance performance reflects subject bias toward a stimulus category or the influence of haptic memory of stimuli presented in Task 1, or a combination of both. Note that during Passive Playback I trials, neither biases nor memory seemed to greatly affect performance. This suggests that subjects could use information about the relationship of lateral and vertical forces during Passive Playback II trials. More experimentation is needed to clarify this.

After the experiments ended, subjects were asked to compare their subjective experiences when actively and passively touching the virtual surfaces. In particular, they were asked about how realistic the virtual surfaces were to them. In both passive and active modes, three subjects reported that the experience resembled touching a surface, and not only experiencing lateral forces. One subject reported that, during active exploration, the stimuli were very realistic, but that during passive presentation they were not. In this case, the stimuli felt just like forces that pulled/pushed the finger of the subject.

6. Acknowledgements.

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7. References.

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