Haptic Discrimination of Perturbing Fields and Object Boundaries

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Abstract

Experiments were performed to reveal how humans acquire information about the shape and mechanical properties of surfaces through touch and how this information affects the execution of trajectories over the surface. Subjects were instructed to make reaching movements between points lying on the boundary of a virtual planar disk object of varying stiffness. It was found that subjects' trajectory adaptation was dependent on the stiffness of the object. When the virtual boundary exceeded a threshold stiffness, subjects adapted by learning to produce a smooth trajectory on the object boundary, while at lower stiffness they adapted by recovering their original kinematic pattern of movement in free space. This adaptation suggests the internal representation of two distinct categories through a continuum of force fields: force perturbations and object boundaries. In the first case, the interaction forces are opposed and the trajectory is restored. In the second case, the trajectory is modified so as to reduce the interaction forces.

1. Introduction

The ability to discriminate an object's mechanical properties from touch is one of the most fundamental somatosensory functions. When manually exploring the mechanical properties of an object, such as stiffness and viscosity, humans probe the object and obtain information from the many sensory receptors in their upper limbs. This sensory information is implicitly incorporated into the actions of the human. For example, when navigating a room in total darkness, one may run one's hand along the surface of a wall while moving through the room, so as to obtain a general idea of the direction of movement and the location of any obstacles along the path.

Information about the mechanical properties of an object is acquired through active haptic discrimination, or active touch. During haptic discrimination the sensory receptors used to discriminate mechanical properties of objects can be divided into two functional classes: kinesthetic (subcutaneous) and tactile (cutaneous) sensors [1]. Kinesthetic information refers to geometric, kinetic, and force information about the limbs, such as position and velocity of joints, actuation forces, and joint interaction forces. These signals are mediated by sensory receptors in muscles, articular cartilage, and tendons. Tactile or cutaneous information refers to shear, pressure, and indentation distributions over the skin. These signals are mediated by mechanoreceptors innervating the dermis and epidermis[2]. During active haptic discrimination individuals acquire and process information from these sensory receptors in order to learn object features.

A number of studies have been performed to understand the perception of shape through active touch. Kappers et al found that humans are capable of learning and distinguishing slight differences in the shape index and curvature of various surfaces [3]. Investigation of actively touched curved surfaces has shown that adaptation and after-effects are present following haptic exploration [4]. These haptic after-effects are manifested as flat surfaces being judged as convex following the touching of a concave surface, and flat surfaces being judged as concave following the touching of a convex surface. Haptic after-effects were found to increase with the time of contact with the curved surface, until effect saturation occurred, and decrease with the time elapsed between the touching of the first surface and the next [5].

Psychophysical studies have also been performed to determine thresholds for stiffness discrimination. Using a contralateral limb matching procedure in which subjects adjusted the stiffness of a motor connected to one arm until it was perceived to be the same as that connected to the other arm, Jones and Hunter determined that the sensitivity of stiffness discrimination is less than the sensitivities for force discrimination and displacement discrimination [6]. This poor sensitivity to stiffness discrimination was much worse than would be expected by combining the sensitivities for force and displacement discrimination.

Experiments were performed to reveal how healthy humans acquire information about the shape and mechanical properties of objects through touch and how this information affects the execution of hand movements over the object. In these experiments, subjects executed hand movements while holding a device that rendered planar disk objects with variable radius and mechanical properties. It was hypothesized that the adaptation to object mechanics will vary depending on stiffness. Particularly, when the boundary exceeds a stiffness threshold, subjects will classify the mechanical force field as an object boundary and adapt by learning to produce a smooth trajectory on the surface. In contrast, at lower stiffness they will classify the force field as a predictable disturbance and will adapt by recovering their original kinematic pattern of movement in free space. Further, it was hypothesized that repeated movements of the hand over a curved boundary would lead to an adaptive process and that this adaptation would reveal, through the change in movement trajectories, an autonomic and implicit learning of object geometry.

2. Materials and Methods

2.1. Experimental Apparatus

All experiments were performed using a two degree of freedom planar manipulandum as seen in Figure 1. Subjects made goal-directed movements in the plane of the manipulandum while grasping its handle. The manipulandum is similar to those previously described [7, 8]. It is instrumented with positional encoders which record angular position of its links. Position and velocity of the manipulandum handle are computed from these encoder signals. These signals are sampled continually at a frequency of 100 Hz. The manipulandum is also equipped with two torque motors that generated the force fields corresponding to the virtual object. Endpoint forces are acquired using a six degree of freedom load cell fixed to the handle of the robot.

2.2. Virtual Object

The force fields experienced by subjects were defined by the following formula:

$$F(r) = \begin{cases} K(R-r) + B\dot{r} & r \le R \\ 0 & r > R \end{cases} \qquad (2.1)$$

This formulation defines a circular, elastic, virtual disk of radius R centered at O. The interface force produced when contacting the virtual disk was proportional to the stiffness of the disk K and the displacement into the boundary r. A component of damping B was incorporated into this formulation to alleviate instabilities encountered at higher stiffnesses. This is a technique commonly used when programming virtual surfaces[9].

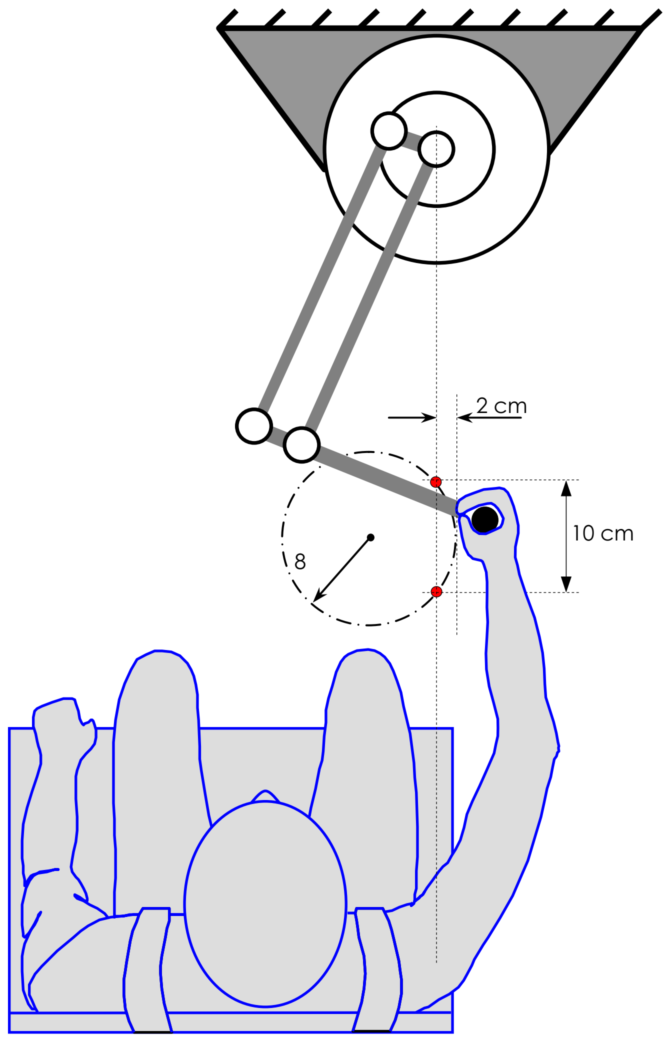

Figure 1. Schematic of manipulandum and dimensions of virtual surface.

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2.3 Experimental Protocol

Subjects made goal directed reaching movements from a start target to a goal target. During a given trial a target was projected onto the subject's workspace and the subject was asked to make one continuous movement to place a cursor registered to the manipulandum handle within the target, while achieving a desired maximum velocity. The next target appeared after the subject held the cursor at the prior target for one second. Subjects were given feedback if they moved faster or slower than the desired maximum velocity. The optimal speed was specified prior to each experiment. When subjects achieved a maximum velocity more than 5% faster than the desired maximum velocity the target turned green. If the target was reached more than 5% slower than the maximum desired velocity the target turned blue. When the target was reached within the desired velocity window the target was animated to explode and a quacking noise was presented as a reward. These feedback cues allowed subjects to achieve a consistent maximum speed of movement of 0.40 m/s.

Prior to the introduction of force fields subjects practiced making point to point movements under the required velocity constraints, in the absence of a virtual object, for 60 movements. In order to assess the typical performance of the subject, undisturbed in free space, objects were not introduced during this baseline unperturbed phase. This phase of the experiment allowed subjects to familiarize themselves with the dynamics of the manipulandum.

Following the baseline unperturbed phase virtual objects were presented to the subject. Subjects were only given a haptic presentation of the virtual object; visual information regarding the geometry of the object was not presented. The dimensions of the virtual object can be seen in Figure 1. A testing phase consisted of the subject moving between targets located on the boundary of the virtual object. Subjects made 100 reaching movements between the presented start and goal positions. The first 50 movements of a testing phase served as a learning period for the subject to acquire information about the virtual surface. During the final 50 movements of the phase catch trials were introduced pseudorandomly for 12.5% of the movements. These catch trials, movements during which no force field was present, were introduced to reveal any adaptations of the feedforward motor command that may have occurred after training with the virtual object.

After completion of the phase consisting of 100 movements with the virtual object was completed a phase consisting of 50 movements in a null field was introduced. This phase allowed for de-adaptation and unlearning of the field encountered during the previous phase. This protocol was repeated for all stiffness levels (K = 200, 400, 800, 1600, 2000). The stiffness levels were presented in order of increasing magnitude. A schematic of the testing protocol can be seen in Figure 2.

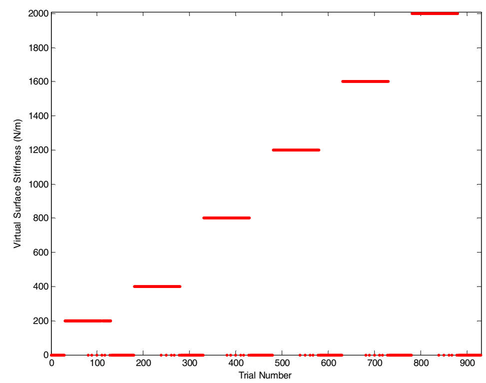

Figure 2. Testing Protocol.

2.4. Trajectory Analysis

Several measures were used to quantify subjects' response to virtual objects and their subsequent learning.

2.4.1 Area Reaching Deviation

The measure of "area reaching deviation" was used to evaluate a subjects' deviation from a straight line path, due to the exposure of a virtual surface,. This measure was defined as the signed area between the trial trajectory and a reference straight line path between the start and goal positions. Area reaching deviation is the spatial average of the lateral deviation away from the reference straight line trajectory. Trajectories to the right of the reference straight line trajectory were given positive weight, while those to the left were given a negative weight.

$$A = \int_{y_i}^{y_f} x \, dy \qquad (2.2)$$

2.4.2 Jerk

Flash and Hogan proposed that voluntary arm movements are executed with the objective of minimizing the time integral of the square of the magnitude of jerk [10]. This cost function defined by Equation 2.3 was used to evaluate the smoothness of subjects' movements while contacting a virtual object..

$$(2.3) \qquad C = \frac{1}{2}\int_0^{t_f}\left(\frac{d^3x}{d^3t}\right)^2 + \left(\frac{d^3y}{d^3t}\right)^2 dt$$

This hypothesis is called the "minimum jerk" hypothesis. The minimum jerk model is based solely on the kinematics of movement ignoring the dynamics of the musculoskeletal system. The minimum jerk hypothesis has been shown to fit simple continuous movements quite well.

2.4.3 Interface Force

The measure of interface force was used to evaluate the forces imparted by the virtual object during subjects' movements. Force samples were acquired from the 6 degree of freedom force sensor affixed to the handle of the manipulandum. These force samples were integrated over the duration of the movement to acquire a resulting force cost (Equation 2.4) for an entire reaching movement.

$$(2.4) \qquad C = \frac{\int_{t_i}^{t_f} F(r,t)\, dt}{t_f - t_i}$$

3. Results and Discussion

A typical set of movement trajectories with the various surface stiffnesses and for different stages of exposure (early exposure, mid exposure, and late exposure) can be seen in Figure 3. For low stiffness disks (200 N/m, 400 N/m), in the early exposure phase, it can be seen that the effect of the virtual object on the hand trajectory of the subject was quite significant and could be divided into two parts. During the first part the hand was driven off course by the object and forced away from the object boundary. At the end of this first part of movement the force field of the virtual object had caused the hand to veer off direction from the target before making a second movement back towards the target.

This is a similar result as to that found for hand trajectories prior to the adaptation of velocity dependent force fields[7]. In studies of these adaptations it has been hypothesized that the hook shaped movements are "corrective movements" that are generated to compensate for errors caused by the unexpected forces. It has been hypothesized that these corrective movements are consistent with the operation of a controller that is attempting to move the endpoint along a desired trajectory bringing it to a specified target position. Since the hypothesized controller uses muscle viscoelastic properties to define an attractor region about the desired trajectory, the hand is eventually brought back to vicinity close to the target position. The hooks result from the interaction of the viscoelastic properties of the muscles and the force field that perturbs the system from its desired trajectory.

In Figure 3 it can be seen that after adaptation subjects produced straight-line movements through the field. This result is further manifested by looking at the pre- and post- adaptation area reaching deviation. Figure 4a shows that the pre and post adaptation area reaching deviation for 200 and 400 N/m were significantly different ($p<0.05$) after learning. Further, the area reaching deviation was reduced to nearly zero, indicating that subjects were producing straight line movements. The ability to produce straight line movements after force field adaptation is indicative of subjects' formation of an internal model to compensate for the dynamics encountered during force field interaction.

After effects from the low stiffness field adaptation show more evidence of the development of internal models similar to those found during velocity dependent force field adaptation studies[7]. These after affects are characterized as being the mirror image of the initial field exposure. This suggests that in the presence of low stiffness position dependent force fields, the subjects adapt by creating an internal model that approximates the dynamics of the environment. This model is used by the nervous system to predict and compensate for the forces imposed by the environment, which results in a negative after effect during catch trials.

Adaptation to force fields of stiffness higher than 400 N/m (i.e. K = 800, 1200, 1600, 2000 N/m) resulted in a different outcome than generally seen during force field adaptation studies.

As in the case of the low stiffness adaptation, initial exposure to the field resulted in a two segment movement with the first portion corresponding to the hand being perturbed off course by the force field and forced away from the boundary of the virtual object (See Figure 3). At the end of this first part of movement the field had caused the hand to veer off direction before making a second movement back towards the target.

Unlike the adaptation seen with low stiffness fields, the higher stiffnesses adaptation did not result in subjects recovering straight line movements. During mid and late

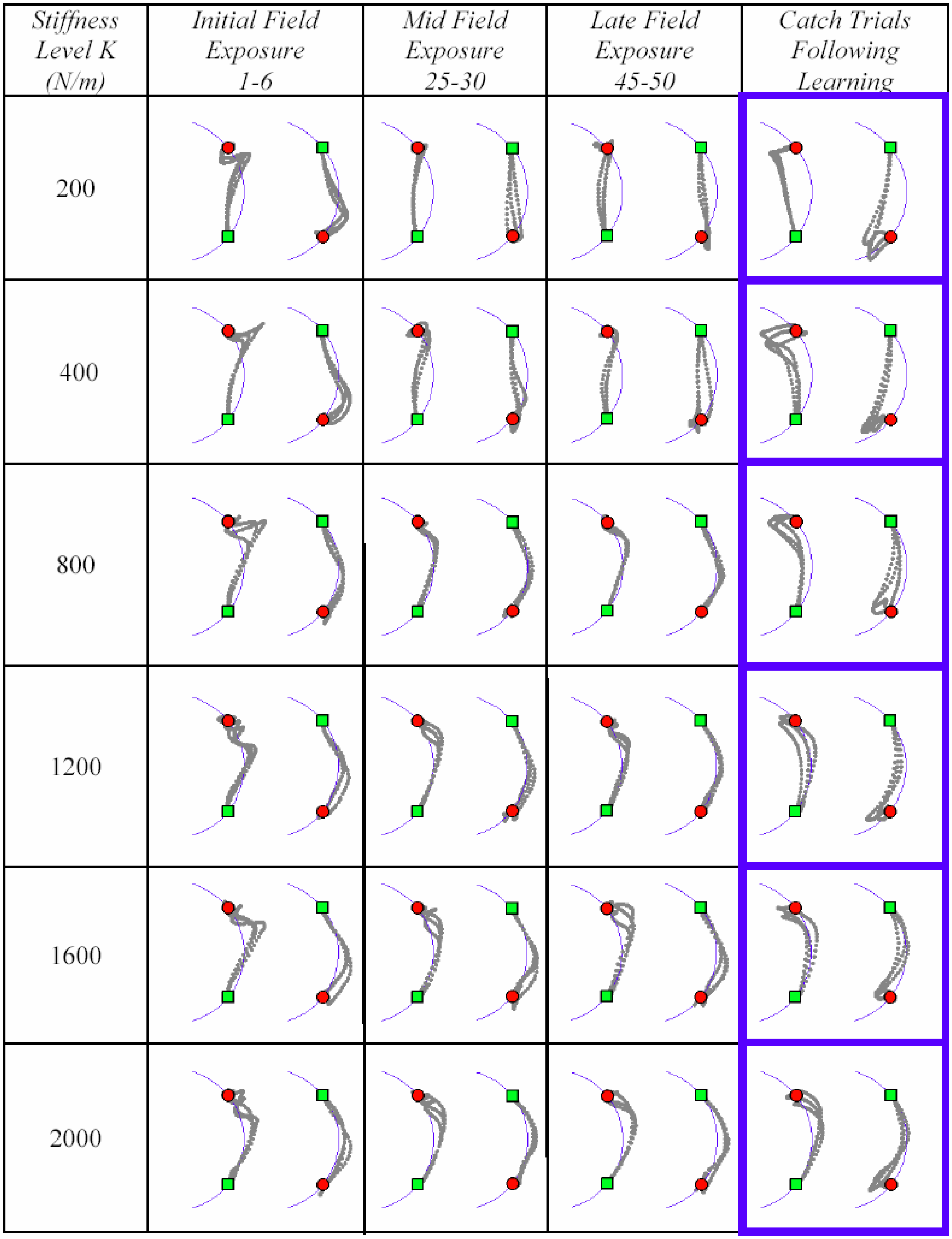

Figure 3. Trajectories from various stages of adaption for a typical subject. Green squares represent the start position, red circles represent the goal position.

exposure subjects produced movements that followed the curvature profile of the virtual surface. At stiffness greater than 400 N/m, after adaptation, subjects' data showed statistically significant decreases in interface force and jerk (Figures 4b, 4c). This indicates that subjects reduced their penetration into the surface, and their resulting compensatory movements after adaptation were smooth over the surface.

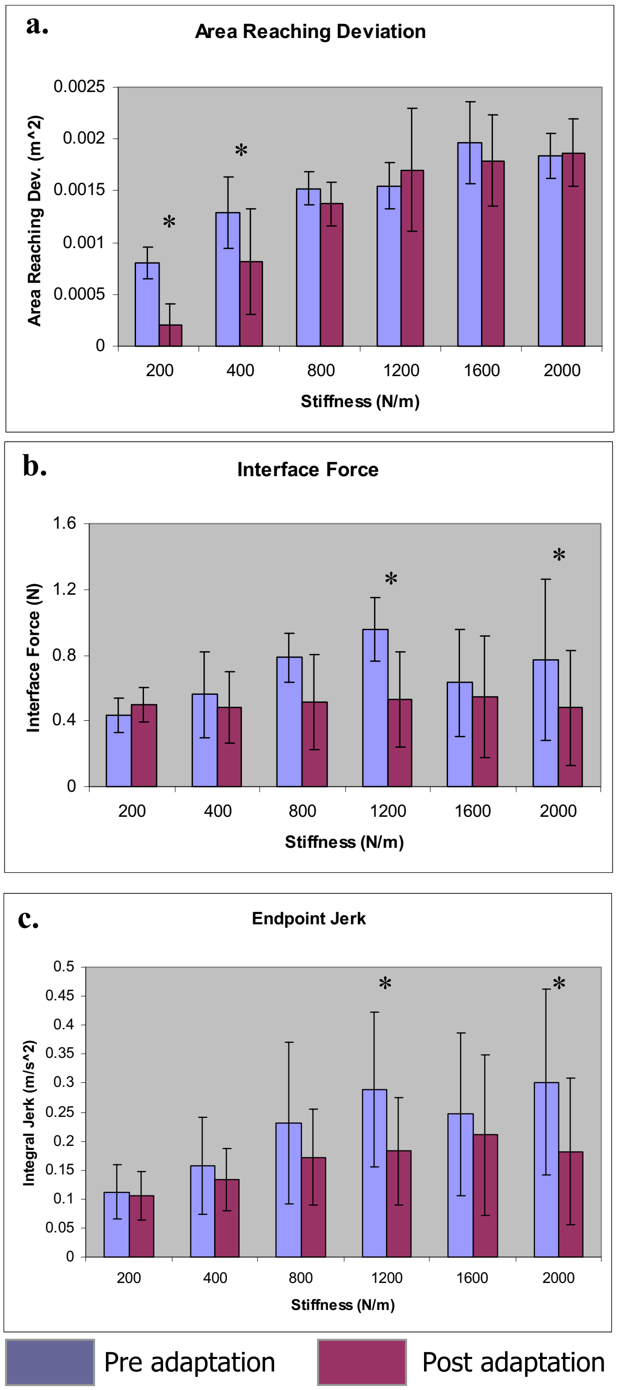

Figure 4. Adaptation data for trajectories, averaged for the early learning phase (pre adaptation) and for the late learning phase (post adaptation).

After effects from catch trials at these higher stiffness levels further show the difference in adaptation between low stiffness and high stiffness fields (Figures 5). At lower stiffness levels the area reaching deviation for catch trials is negative, indicating a negative after effect, and thus an adaptation which compensates for the field dynamics and results in straight line movements. At higher stiffness levels this is not the case. Once a stiffness threshold is exceeded subjects' area reaching deviation for after effects is positive, indicating after effects in the direction of the applied forces and following the profile of the virtual boundary. The magnitude of this positive after effect increases with increasing stiffness. Below the stiffness threshold the magnitude of the negative after effect increases with decreasing stiffness.

3.1. A Possible Interaction Strategy

While the visual appearances of trajectories at various values of stiffness can be seen to vary greatly after the threshold of object boundary detection is reached, a unifying feature amongst these trajectories is integral interface force. Through the continuum of virtual surface stiffness levels subjects produce similar integral interface forces after adaptation (Figure 4b). A two factor ANOVA without replication did not find a significant difference amongst the six stiffness levels, for subjects, after adaptation had occurred.

It can be seen that at low stiffness (200 N/m) subjects produce a higher average interface force after adaptation as compared to interface forces observed before adaptation. Further at low stiffness levels (200 N/m, 400 N/m) significant differences were found between the area reaching error pre and post adaptation. Subjects reduced the area reaching error after adaptation at these low stiffness levels. This implies that at low stiffness subjects formulate an internal representation of the virtual surface, as they reduce their deviation from a straight-line path. This internal representation appears to be similar to those described in previous force field adaptation experiments in that ability to recover a straight-line movement after adaptation is indicative of an internal model that is able to completely compensate for the dynamics encountered during force field interaction.

At the higher stiffness levels subjects abandoned the goal of reducing straight line deviations and instead strived to reduce the interface force. Statistically significant reductions in interface force and jerk were found after adaptation at the stiffness levels of 1200 N/m and 2000 N/m. This result implies that at high stiffness subjects

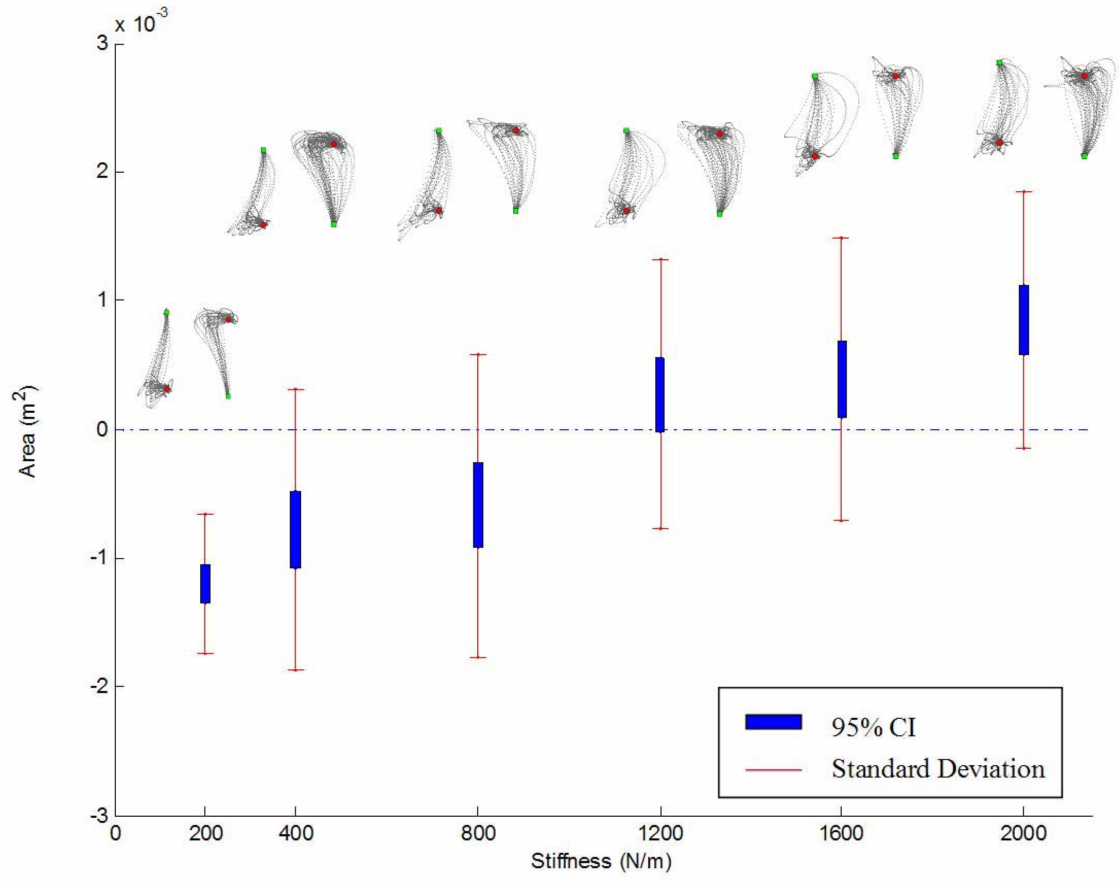

Figure 5. Trajectories and area reaching error averaged for all subjects' catch trials.

form an internal representation of the virtual boundary based on the reduction of the interface force to a baseline value and the goal of producing a smooth movement over the boundary. In essence subjects encountered the boundary and to some extent complied with its shape while producing smooth movements .

4. Conclusions

It was found that subjects' trajectory adaptation was dependent on the stiffness of the field that implemented the virtual object and its boundary. When an object exceeded a threshold stiffness of 1200 ± 205 N/m, subjects adapted by learning to produce a smooth trajectory on the boundary, while at lower stiffness they adapted by recovering their original kinematic pattern of movement in free space. This adaptation suggests the internal representation of two distinct categories through a continuum of force fields: force perturbations and object boundaries. In the first case, the interaction forces are opposed and the trajectory is restored. In the second case, the trajectory is modified so as to reduce the interaction forces and produce a smooth movement is reprogrammed to take place over the object's boundary. A unifying theme through the continuum of force fields is the integral interface force. Results show that subjects produce a consistent nominal interface force after adaptation, regardless of the stiffness of the object with which they are interacting. This indicates that a possible goal of interaction could be to maintain a level of force contact with the object to aid in the guidance of motion within or along its boundary.

Acknowledgements

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