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Midpoint Perturbation Response in Haptically-Guided Movements

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Abstract—**This study investigates the human response to impulse perturbations at the midpoint of a haptically-guided straight-line point-to-point movement. Such perturbation response may be used as an assessment tool during robot-mediated neuro-rehabilitation therapy. Subjects show variety in their perturbation responses. Movements with a lower perturbation displacement exhibit high frequency oscillations, indicative of increased joint stiffness. Equally, movements with a high perturbation displacement exhibit lower frequency oscillations with higher amplitude and a longer settling time. Some subjects show unexpected transients during the perturbation impulse, which may be caused by complex joint interactions in the hand and arm.**

I. Introduction

HAPTICS refers to the capability to sense a natural or synthetic mechanical environment through touch. Haptics also includes kinaesthesia (or proprioception) – the ability to perceive one's body position, movement and weight [1]. A haptic computer interface is a device that allows people to interact with a computer through the sense of touch. Unlike traditional interfaces, haptic interfaces generate mechanical feedback that can be felt by the user. The feedback can be provided through a robotic arm, where the user holds a stylus or places a finger into a thimble attached to the end of the robot (Fig. 1).

With haptic *guidance*, forces are generated through the haptic device to lead the user along a given trajectory in order to allow them to experience an 'ideal' motion. Haptic guidance has been used in training and rehabilitation. For training, haptic guidance has been shown to be effective in helping people to learn complex motor skills, with greater benefits than visual learning alone [2], [3]. In rehabilitation, haptic guidance has been used to assist people in performing motor tasks that are difficult or impossible for them to perform independently, as a way for them to re-learn lost motor skills [4], [5].

For rehabilitation applications, there is a need for simple but objective measures of motor recovery. In this paper, we investigate a person's response to a perturbation as a potential measure of recovery during rehabilitation involving haptically-guided movements. Movement perturbations have been studied previously for *unguided* reaching movements, for example, to study motor adaptation to constant [6] and transient [7] perturbation forces. While haptic guidance and perturbation responses have been studied independently in the past, no significant studies have been conducted on perturbations during guided movements.

This paper presents a study of the response of healthy subjects to an orthogonal perturbation impulse at the mid-point of a point-to-point guided movement. The aim is to identify aspects of the response that may be of interest in using perturbations to assess motor recovery during rehabilitation involving haptic-guidance.

An experimental environment was developed in which the user's hand movement was guided along a point-to-point Minimum Jerk Trajectory (described in Section II). Some movements were perturbed at their midpoint by an orthogonal impulse in the saggital plane. Visual feedback was given throughout the movement by a 3D scene on a computer monitor (Fig. 2), showing the trajectory start and end points, as well as the end-effector. Position data were gathered during the movement for later analysis.

II. Minimum Jerk Trajectory (MJT)

A point-to-point trajectory defines the route taken from one point to another, as well as the velocity at any given moment. In voluntary multi-joint reaching movements, humans naturally follow a straight-line trajectory with a bell-shaped velocity profile.

Minimum Jerk Trajectory (MJT) is one of the techniques for mathematically generating a smooth trajectory. A 7th order polynomial is used to represent displacement, x, with respect to time, t, and the polynomial coefficients are tuned to minimize the jerk parameter, J, for the duration of the movement, d, as shown in (1).

$$J = \int_0^d \left| \frac{d^3 x}{dt^3} \right|^2 dt \qquad (1)$$

Details of the procedure for constructing the polynomial are in [8]. The resultant trajectory has the displacement and velocity characteristics shown in Fig. 3.

During guidance, the end-effector of the haptic device is pulled towards the current point on the ideal trajectory by a simulated spring force (stiffness 0.7N/mm). Movement along the ideal trajectory results in no force output, but any deviation from the trajectory results in a restoring force proportional to the magnitude of the deviation.

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II. Implementation

Software was developed to conduct a point-to-point guided movement using Minimum Jerk Trajectory and, optionally, introduce a disturbance impulse at the midpoint of the movement. Visual feedback during the experiment is provided by rendering a 3D scene.

A. Haptic Interface

The haptic interface used for this study was the PHANTOM Premium 1.5 device from SensAble Technologies (www.sensable.com), shown in Fig. 1. It provides three powered degrees of freedom; this study was only conducted in the transverse plane (left-right; towards-away). The third dimension (up-down) was restricted by way of a *tabletop effect*, which prevents movement below a given horizontal plane (akin to resting a pen on a tabletop).

Fig. 1. The SensAble PHANTOM Premium 1.5 haptic interface was used for the experiments in this study.

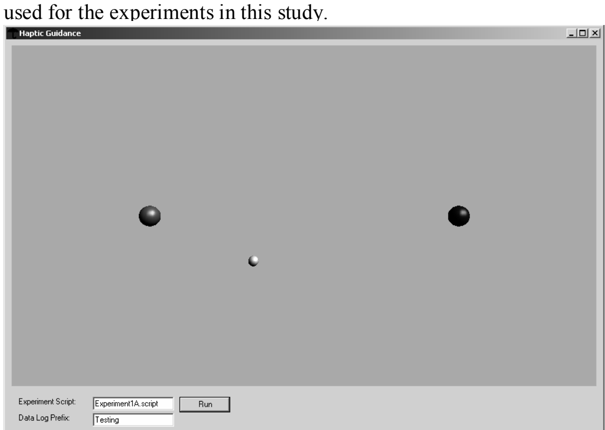

Fig. 2. The 3D scene presented to a subject shows the relative position of the end-effector, and the trajectory start and end points.

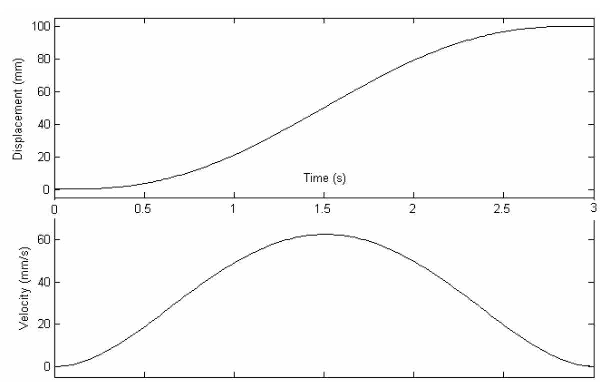

Fig. 3. MJT for a 100mm movement lasting 3 seconds. The velocity profile features the characteristic bell-curve shape.

B. Software

Low-level control of the PHANTOM was provided by the OpenHaptics Toolkit from SensAble. The desired haptic effects (MJT, Tabletop Effect) and data-logging were implemented in a hardware independent abstraction layer using C++. This was then compiled to a reusable Dynamic Link Library (DLL). The GUI was implemented in C# using the Microsoft .NET Framework and Managed Direct3D (DirectX 9) for 3D graphics rendering.

III. Methods

The subject was seated in front of a computer monitor with their right index-finger in the thimble of the PHANTOM, and their right elbow aligned with the base of the PHANTOM.

The task involved moving their arm to the starting-point – 150mm to the left of the central position – and dwelling at the on-screen marker sphere for 200ms. The Minimum Jerk Trajectory guidance was then activated, guiding them to the end-point marker sphere – 150mm to the right of the central position – in a time of 1s. After a 200ms dwell time at the end marker, guidance was switched off. The subject was then free to return to the starting-point in their own time for the next movement.

On some movements a perturbation impulse – of strength 2.5N and duration 50ms – was introduced when the end-effector reached the central position in the guided movement. The perturbation was in the saggital plane, in a direction orthogonal to the guidance trajectory (i.e. either towards or away from the body). No guidance was provided in the axis of the impulse for the duration of the perturbation. During each movement the position of the end effector was logged with a frequency of 1000Hz.

Subjects were advised that some movements would be perturbed, but they were given no advice on how to deal with perturbations. No stipulation was made that, for instance, subjects should try to minimize the effect of perturbations.

For this experiment, each subject completed a block of 60 consecutive guided movements, as follows:

12 movements with no perturbation
12 with a mid-point perturbation in one direction
12 unperturbed movements
12 with perturbation in the opposite direction
12 unperturbed movements

Experiments were conducted on seven male subjects in their early-to-mid twenties who had no apparent motor skill impairments. Two of the subjects had previous experience in using the PHANTOM device. The order in which the direction of perturbation was presented was counterbalanced across subjects.

IV. Results

The data collected from experiments was analyzed by plotting y-coordinates from the transverse plane against time. Results for Subject 7 are shown in Fig 4 and are typical of several subjects. The perturbation impulse causes an increasing displacement of the end-effector for 50ms until the impulse is switched off, and the subject recovers to the trajectory (with the help of guidance). It is interesting to note that Subject 7 has a clear asymmetry in the magnitude of perturbation displacements – perturbations away from the body have a greater impact in displacing the end-effector. This is somewhat unusual, as all other subjects either showed a clear bias in the opposite direction, or had roughly equal displacement magnitude in both directions.

The magnitude of the displacement caused by perturbations was highly variable for most subjects, and uncorrelated with the trial sequence – magnitude of displacement did not decrease with the progress of trials; no adaptation was apparent.

Subjects with lower perturbation displacement exhibited high frequency oscillatory transients both during the perturbation and in their recovery from the perturbation. Results from one such subject are shown in Fig. 5.

Most subjects had never used a haptic interface before, and each had an interesting approach to the experiment: some subjects held their index finger perfectly straight and horizontal; some had a slight bend at the middle knuckle; and some had a 90 degree bend at the middle knuckle, with their finger entering the thimble vertically.

In addition, although the position of the end-effector was only logged during the guided movement, a lot of variation was observed in the techniques subjects employed for returning to the start point after each movement. Some subjects had a natural inclination to loop back to the start in a curved movement along the saggital plane and some did the same movement in the transverse plane. Eventually, all subjects adopted a straight-line return path along the trajectory axis.

V. Discussion

One key point observed was that subjects did not exhibit adaptation to the perturbations. This may have been due to the short (50ms) duration of perturbations, which limited their displacement of the end-effector. No subject showed more than 30mm orthogonal deviation from the axis of their 300mm movement, so it is arguable that the impact of perturbations was small enough not to warrant suppression. It is also possible that twelve movements did not allow enough time for adaptation to have a noticeable effect.

An intentional aspect of the study was not to provide experimental subjects with any advice on dealing with the perturbations. This gives us an idea of how much variation there is in the natural perturbation response across various healthy people. It is also likely that this lack of objective, for the subject, gave them little incentive to adapt to perturbations. Subjects could happily go along with the

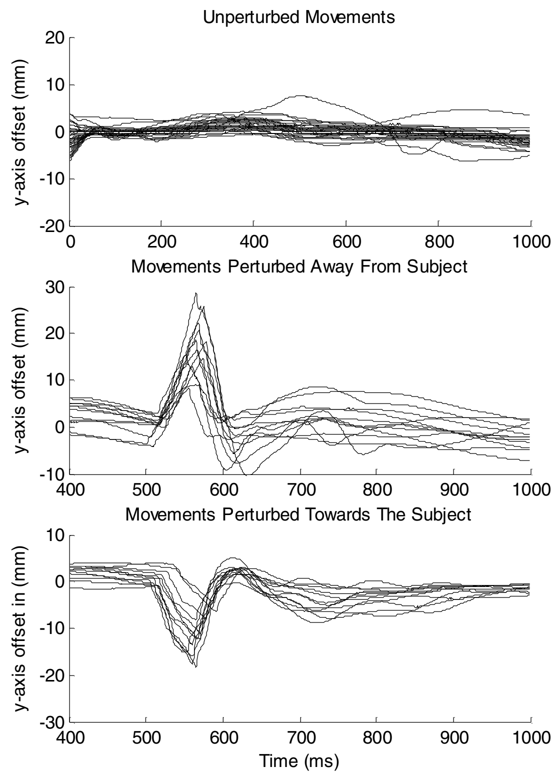

Fig. 4. Displacement in the y-axis of the transverse plane for all sixty movements of Subject7. The displacement during perturbed movements shows a bias toward perturbations away from the subject.

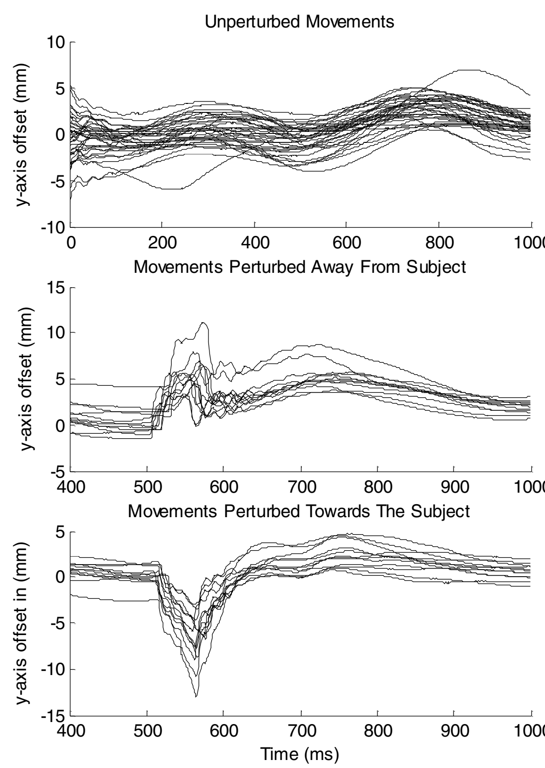

Fig. 5. Subject 5 had a lower magnitude displacement featuring high-frequency oscillatory transients during and after the perturbation. (Note the y-axis scales differ with those in Fig. 4 by a factor of two.)

movement and any perturbations, knowing that the guidance would eventually take them to the correct end-point regardless.

Subjects exhibiting a lower displacement magnitude consistently showed high frequency oscillatory transients both during and after the perturbation (Fig. 5). These oscillations may be indicative of increased joint stiffness. Conversely, subjects exhibiting higher displacement magnitude showed lower frequency oscillations, of higher magnitude, after the perturbation.

The unusual transients taking place during the perturbations in Fig. 5 could be caused by joint movement in the index finger. If the index finger is held straight horizontally, then bent at ninety degrees at the second knuckle, and inserted vertically into the thimble, joint movement in the index finger alone can provide a small amount of 'reach', away from the body. Initially there is little resistance to the perturbation as the index finger accommodates the displacement without involving any other joints. Once at the limit of this reach, the wrist, elbow, and shoulder joints enter the movement and slow down the displacement while the entire arm is accelerated.

A lot of this variation between subjects may have been caused by differences in their use of the PHANTOM device (e.g. orientation of index finger), and their differing techniques in the experiments. For example, a perfectly straight index finger held horizontally would naturally provide high stiffness and transmit perturbations through the hand to the elbow. This would provide far higher perturbation damping than an index finger bent at 90 degrees to enter the thimble vertically.

VI. CONCLUSION

For orthogonal perturbation pulses of short duration subjects showed a wide variety of response characteristics. Those with a smaller perturbation displacement had transient oscillations of a higher frequency during and after the perturbation impulse.

Subjects who had not used a haptic interface previously showed a variety of approaches in using the interface outside of guided movements.

The magnitude of perturbation displacement may have been exaggerated as subjects were *not* instructed to try to minimize the effect of disturbances.

VII. FUTURE WORK

Currently, guidance is provided in both axes of the saggital plane, which means the user receives guidance in the axis of the perturbation and is able to complete the task without any active movement. Future research will investigate users' responses when guidance is provided only in the forward direction, i.e. the haptic device pulls forward to the x-coordinate of the end target but leaves the y-axis unguided. The movement would again start and end at fixed (x,y) coordinates, and the subject would again be perturbed in the y-direction and left to recover to the target y-position. This would mandate active intervention from the subject in order to reach the target end-point.

The findings from this study suggest that further studies are required to determine if the variability within and across subjects can be reduced when interactions with the haptic interface are more consistent (e.g. more precise wrist and finger positioning; or the use of a gravity compensation device for the arm). This would allow for the development of more reliable measures of recovery.

Finally, although this study has provided initial insights into the characteristics of users' responses to movement perturbations, for assessing motor recovery during rehabilitation, further studies involving people with motion impairments are required.

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