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Motor adaptation to Coriolis and contact forces

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Objective

A rotating space vehicle could be used to generate "artificial gravity" during long-duration missions, but this would have side effects. Movements made during body rotation would generate transient Coriolis forces that act perpendicular to both the rotation axis and the movement direction. We have found that such Coriolis forces initially deviate the trajectories and endpoints of reaching movements but adaptation occurs to restore accuracy if exposure continues. The patterns of movement deviation generated by Coriolis forces differ from those observed when movements are perturbed by external, mechanical contact forces of comparable timing and magnitude. This implies that cutaneous contact cues are critical in the control and monitoring of movement endpoint, trajectory, and adaptation. Our goal was to investigate the conjoint influence on reaching and adaptation of cutaneous sensory signals, proprioceptors, and efferent commands. We measured the effect on reaching movements of exposure to contact force perturbations, non-contact Coriolis forces, and combinations of the two. Acquisition, retention, and transfer of adaptation was also be studied. The results allowed us to refine our model of the adaptation, planning, and execution of reaching movements. This provided a basis for anticipating and solving potential performance problems in a rotating artificial gravity environment.

Background

This three-year project ended in FY01. Our FY01 work was based on previous results which had shown that 1) reaching movements to targets are deviated by Coriolis forces and mechanical contact forces; 2) both types of perturbations generate errors in reaching paths and endpoints in the direction of the perturbing forces; 3) adaptation of movement endpoint and movement path are dissociable; 4) endpoint adaptation occur rapidly with additional movements even in the absence of visual error feedback so long as the hand makes contact with a surface at the end of the movement; 5) there are no aftereffects from adaptation to mechanically induced errors when the subjects' arms are no longer attached to the apparatus, however, after adaptation to Coriolis force perturbations when the slow rotation room was again at rest subjects showed large aftereffects in pointing to targets. 6) There is partial cross-transfer between inertial Coriolis force perturbations and mechanical contact force perturbations. This indicates that adaptation to mechanical contact forces is context specific. 7) If the hand is maintained in contact with a surface while moving to point to a target during rotation, adaptation to the Coriolis force will occur for movement trajectory but not movement endpoint if visual feedback is denied.

Results

One of our accomplishments in FY01 was to study the context specificity of adaptation of movement path to Coriolis and contact forces present during the transport phase of an arm movement Our strategy was to study the paths of three types of movements - forward arm extension during passive rotation in the rotating room, forward arm extension during active torso rotation, forward reaches perturbed by a mechanical linkage attached to the arm. All analyses looked at finger trajectories (as in past research) as well as joint angle and torque profiles. While fingertip trajectory was similarly affected in all three conditions, the patterns of joint angle deviation and joint torque compensation differed. The two cases involving inertial perturbations (reaching during active and passive torso rotation) showed greater deviations at the shoulder and less at the elbow relative to the conditions with mechanical perturbation of the hand. This may be the basis of context specific adaptation.

A second accomplishment in FY01 was studying the landing forces of reaches in a normal stationary environment. The spatial orientations of shear force vectors registered on a force platform contacted by the finger at the end of reaches were a systematic function of where the finger landed. These vectors converged at a point near the shoulder of the reaching arm. The landing force vectors did not correlate with the finger's terminal velocity or with its angular position projected onto a horizontal plane. Thus, shear force direction on the fingertip maps finger spatial position in shoulder coordinates. We had previously shown that in intact subjects in the rotating room adaptation restores reaching endpoint and path to normal if the finger touches down, but only curvature adapted to baseline if reaches ended with the finger in the air or if the subject lacked vestibular function. In the stationary reach-and-touch paradigm, all vestibularly intact subjects showed the same mapping of contact force to reaching endpoint but a subject without vestibular function showed no systematic relationship. Preliminary analysis of parabolic flight experiments indicate that the reaching endpoint is signaled by terminal contact cues in non-terrestrial environments. These results demonstrate the contribution of mechanically non-supportive contact cues to calibration of proprioception, motor control and spatial orientation in terrestrial and space environments.

Significance

Work on rotating artificial gravity environments has enlightened us about the presence of Coriolis and other inertial accelerations on the arms and legs during self-generated, voluntary movements in a normal terrestrial environment. Initial measurements have shown that Coriolis forces on the hand during natural turning and reaching movements are greater than in our rotating room experiments, yet the hand reaches its goal accurately and the Coriolis forces are not noticed. We would like to examine the form of this automatic compensation for self-generated forces in a terrestrial environment.

Our current work on adaptive changes in head movement control points to neck proprioceptive as well as vestibular signals being a key factor in the disorientation and motion sickness elicited by head movements during passive body rotation. We had earlier shown that simply altering the effective inertial mass of the head makes voluntary head movements provocative. These findings have significance for understanding the etiology of space motion sickness and motion sickness on Earth. They also have direct significance for understanding why cybersickness occurs in virtual environments. Almost all situations in which motion sickness occurs involve alterations in the normal patterning of eye and head movement control in relation to proprioceptive and vestibular feedback.

The demonstration that light touch is a sensory guide to posture during dynamic perturbations amplifies the importance of our earlier work showing that light touch stabilizes stance under more static conditions. This opens the way for the investigation of touch cues in *mobility* for clinical problems and for circumventing re-entry disturbances in astronauts. Many other investigators are now following up on our pioneering investigations.

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