MOTOR CONTROL AND ADAPTATION IN A ROTATING ARTIFICAL GRAVITY ENVIRONMENT

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INTRODUCTION

One obstacle to the idea of rotating a space vehicle to generate artificial gravity is concern about the side effects of rotation on human sensorimotor control. The most conspicuous side effects in a rotating room are the severely disorienting and nauseogenic consequences of head movements at high room speeds. In early experiments, adapting people to tolerate head movements at rotation rates greater than 3 rpm required great effort and resulted in powerful aftereffects upon return to a non-rotating environment (Guedry, et al., 1964). Generating 1 g of artificial gravity at 3 rpm requires a radius of about 100 meters, which is technically and financially unrealistic (Nicogosian & McCormack, 1987). Approaches to adapting humans to tolerate higher rates of rotation have focussed on vestibular mechanisms. We have investigated the effects of linear Coriolis forces generated in a rotating environment on voluntary arm and leg movements as well as on head movements and posture. The results indicate that adaptation up to 10 rpm can be achieved if exposure history is appropriately controlled.

ARM MOVEMENTS

We have studied subjects making reaching movements before during and after constant velocity 10 rpm counterclockwise (CCW) rotation, in the center of a rotating room. They reached to a light that shone through a translucent table and went off at movement onset, leaving them in total darkness. During rotation, moving the arm or any other appendage generates Coriolis forces proportional to limb velocity, $\vec{F}_{Cor} = -2m(\vec{\omega}\times\vec{v})$, where m is the mass of the moving appendage, $\vec{v}$ its linear velocity and $\vec{\omega}$ the angular velocity of the rotating environment in radians/sec. This means there is not a Coriolis force acting at the very beginning nor at the very end of a movement, but while the arm is extending forward a Coriolis force acts on it, rightward during CCW rotation. (See Figure 1A.) Neither sensory signals about rotation nor significant centrifugal forces are present during constant velocity rotation on subjects in the center of the room, so they feel like they are stationary in a 1 g environment

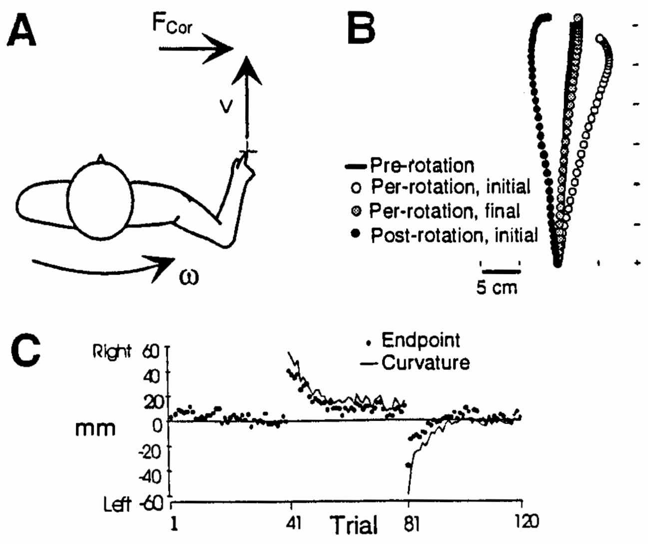

Figure 1. A. Coriolis forces (F_{cor}) generated during reaching movements made while the body is rotating counterclockwise. B. A top view of average reaching movements 11 subjects made in darkness to the position of a just extinguished visual target, before, during and after 10 rpm counterclockwise rotation. C. Average (11 subjects) endpoints and curvatures (deviations from straight line trajectories) of 40 reaching movements (per subject) before, during and after rotation.

before reaching.

We found that subjects' first movements during rotation were abnormally curved and missed the target in the direction of the Coriolis force. Even without sight of their arm subjects adapted completely in 10-20 reaches so that their movements again went straight to the target location. At first they felt they were fighting an external force but when adapted they no longer felt the existence of the Coriolis force acting on their arm. Adaptation was more rapid and complete if at the end of each reach subjects touched down on the table although its surface did not demarcate the target. When rotation ceased, subjects again made reaching errors with the adapted arm, mirror-image to the trajectory and endpoint errors that had originally occurred during rotation. Re-adaptation restored straight accurate reaches at the same rate as adaptation to rotation had. See Figures 1B and 1C, from DiZio & Lackner, 1995.

Perturbations of arm movements were present at rotation speeds of 2.5 to 20 rpm, and there was rapid, complete adaptation at all speeds. If sight of the arm was permitted, Coriolis forces still caused initial errors and aftereffects, but adaptation was more rapid than in darkness. Subjects without vestibular function showed similar patterns of Coriolis force perturbation to normals but adapted less fully. Adaptation of one arm during rotation transferred partially to the arm that was immobile during rotation.

These experiments prove that earlier experiments in rotating artificial gravity environments greatly underestimated the capacity for limb movement adaptation. Cutaneous cues from the finger landing on a surface are crucial for adaptation of movement endpoint. Subjects can adapt reaching movements rapidly to rotation rates much faster than any that would be considered for generating artificial gravity in a spacecraft. Recent experiments on subjects in parabolic flight and at the periphery of the rotating room have validated the original results for predicting effects of rotation in non-1g force backgrounds (Lackner and DiZio, 1998).

LEG MOVEMENTS

We have also studied leg movement control and adaptation in a similar paradigm. Subjects holding hand rails stood on one leg at the center of the rotating room and pointed with the other foot to a visual target on the floor that was extinguished at movement onset. When the room was rotating 10 rpm CCW, rightward Coriolis forces were generated and the movement path and endpoint were deviated right. Adaptation occurred within 20 movements during rotation, followed by symmetric aftereffects and re-adaptation when rotation stopped.

HEAD MOVEMENTS

Previous studies of head-eye coordination and spatial disorientation in a rotating room emphasized vestibular effects and neglected the Coriolis force actions on the head/neck system. We have made the first kinematic measurements of unconstrained pitch head movements during constant velocity rotation, showing perturbations and rapid adaptation. The perturbations involved lateral translatory deviations of path and endpoint as well as deviations in roll in the direction of Coriolis forces on the head. The lateral translations adapted often within 8 movements but the roll component of adaptation was incomplete after 24 movements. These results suggest there are dual adaptation processes involving rapid motor adjustments analogous to arm and leg adaptation to Coriolis forces on the head/neck system and a slower adaptation to vestibular cross-coupled stimulation. Overall functional adaptation may be hastened with controlled exposures that sequentially engage each sub-system.

POSTURE CONTROL

In the rotating room, standing quietly is difficult because of vestibular cross-coupling stimulation and Coriolis forces on the body generated by small random sway movements. We have tested subjects in the center of the rotating room attempting to stand "as stable as possible" with eyes closed and feet placed in tandem. They alternated using light touch (less than 40 grams) of the finger on a stable surface or no touch. Touch approximately halved the normal pre-rotation sway. During 10 rpm rotation subjects without touch swayed to the limits of stability and had to grab the safety rails for support. With touch, rotation did not increase sway over the baseline period. Even patients lacking vestibular function could stand with light touch in darkness during rotation. After only eight 25 sec rotation trials without touch, postural sway post-rotation without touch was significantly greater than baseline. Light touch suppressed this aftereffect. These results show that a highly integrative task like stance adapts quickly to rotation if the proper sensory cues are provided.

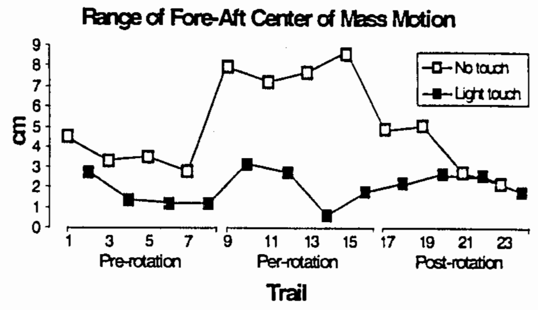

Figure 2. A typical subject's quiet stance performance before, during and after 10 rpm exposure in the center of the rotating room. The conditions were eyes closed, feet positioned in tandem. The range of fore-aft center of mass motion is presented for every trial.

CONCLUSIONS

All the movements studied adapt rapidly to 10 rpm rotation. Even head movements and posture may be fully compensated for rotation up to 10 rpm if the proper adaptation schedules and sensory cues are provided. Light, precision contact is effective for suppressing the effects of making transitions between rotating and non-rotating environments as well as hastening adaptation. Context-specific adaptation is also possible to facilitate transitions between force environments without any adjustment period (Cohn, DiZio & Lackner, forthcoming). Thus, human sensorimotor control is not an obstacle to a relatively short radius space vehicle (20-40 meters) spinning fast enough to provide the benefits of artificial gravity.

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