

SENSORY MOTOR COORDINATION IN AN ARTIFICIAL GRAVITY ENVIRONMENT

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Rotating a space vehicle to generate artificial gravity has long been proposed as a way of preventing bone demineralization, maintaining muscle integrity, and enhancing hygiene during long duration space flight. Recently, a number of deleterious effects of weightlessness on muscle fiber types, motoneurons, vestibular sensory receptors, and immune system function have been identified as well (1, 2, 3). Moreover, it is likely that cortical maps of somatosensation and motor function would be altered during prolonged space flight in the absence of artificial gravity. Such maps have been recently shown to be highly dependent on the environmental sensory-motor demands placed on an animal and to remain plastic throughout life (4). Some of the re-entry disturbances of postural and movement control exhibited by astronauts and cosmonauts may relate to alterations in these maps as well as to changes in muscle strength, fiber types, and innervation.

Artificial gravity achieved by rotation could offset these problems. However, a rotating environment has a number of undesirable side effects. These include, in short radius devices (6-10 meters) especially, gravity gradients, changes in effective weight during locomotion and Coriolis forces. These effects tend toward their asymptotic minima at about a 40 meter radius and are already greatly attenuated at a 20 meter radius (5, 6). In addition, head movements during rotation result in unusual stimulation of the semicircular canals ("cross-coupling") and otolith organs. At higher velocities of rotation, 5 rpm or more, head movements can elicit motion sickness if the individual is brought up to the final dwell velocity in a single step, rather than being allowed to make many head movements at gradually

increased velocities of rotation (7, 8).

It has long been thought that humans would have great difficulty adapting to rates of rotation greater than about 3 rpm. This velocity would require, in order to generate 1 g of artificial gravity, a radius of rotation of approximately 100 meters. This is impractically large except for a tethered type of rotating vehicle. We believe on the basis of our work on adapting limb movement and head movement control to rotation that this is an unrealistically low rate of rotation. Adaptation to 6.7 rpm would allow a radius of 20 meters for 1 g of artificial gravity, and we believe this is quite feasible.

We will summarize here some of our work on adaptation of limb movement control to the Coriolis forces generated by body movements during rotation. Coriolis forces are generated on an object when it moves in a rotating reference frame. The Coriolis force is an inertial force that is proportional to the mass (m) of the moving object, its linear velocity (v) relative to the reference frame, and the velocity of rotation (ω).

$$F_{cor} = -2m(\omega \times v)$$

Figure 1 illustrates what happens when a subject makes a forward reaching movement while seated at the center of a room turning counterclockwise at constant velocity. A rightward Coriolis force is generated that will deflect the path of the subject's reaching movement. The Coriolis force is a transient force, it is absent at the beginning and at the end of the reaching movement because at those times the linear velocity of the arm is zero. Normal reaching movements have a bell-shaped velocity; consequently, the Coriolis force will also have a bell-shaped profile. Interestingly, some of the most prominent current theories of movement control, the α equilibrium point and λ equilibrium point theories (9,10), would predict that reaching movements would be accurate in a rotating environment. These theories would predict that the paths of reaching movements would be deflected but that the endpoints would be accurate. According to the α and λ models movements are controlled by executing a series of changing equilibrium point specifications to the

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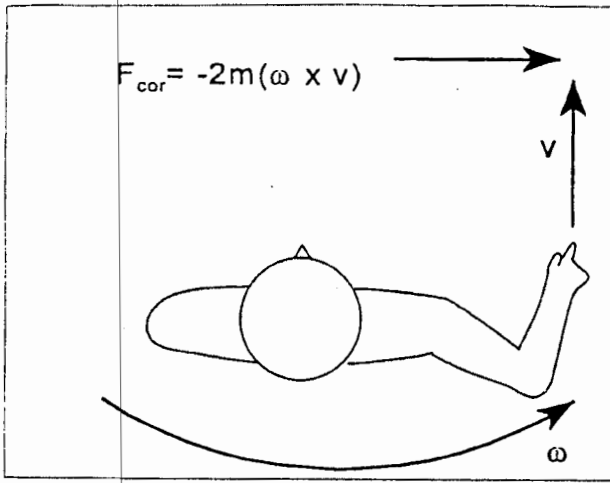


Figure 1. Forward hand movements (velocity, v) generate rightward Coriolis forces (F_{cor}) on the arm during counterclockwise rotation (ω).

muscles controlling the limb. The endpoint is determined by the final programmed length-tension properties of the limb muscles. Since the Coriolis force is present during but absent at the end of the movement, the movement path should be deviated but not the endpoint.

Figure 2 illustrates the experimental paradigm we have used to study the effects of Coriolis forces on reaching movements. The subject is seated at the center of a fully-enclosed rotatable room. A smooth Plexiglas panel extends forward at waist height and serves as a work space for the subject to make reaching movements. Light emitting diodes (LEDs) are embedded in the underside of the Plexiglas and when activated serve as targets to which the subject points.

When the subject depresses a start button on the surface, one of the LEDs is activated, the LED goes out when the subject lifts his finger to point at it. The subject makes 40 reaches prior to rotation, 40 reaches during rotation, and 40 reaches afterwards. The subject does not begin the per-rotation reaches until he has been at constant velocity for 2 minutes, nor the post-rotation ones until he has been at rest for 2 minutes. The pre-rotation reaches serve as an index of baseline accuracy. The initial per-rotation reaches represent an indication of the disruptive effects of Coriolis forces, subsequent

per-rotation reaches a gauge of any adaptive accommodations, and the initial post-rotation reaches are an index of persistence of any adaptation elicited during rotation - all considered in relation to pre-rotation baseline accuracy. The subjects reaching movements are monitored by a video movement analysis system (WATSMART) which enables a kinematic analysis of movement properties.

We have carried out many different studies using the paradigm described above (11, 12). In all of these studies we have used a rotation velocity of 10 rpm. We chose this value because it is equal to or above that likely ever to be used in artificial gravity environments involving free body movements and locomotion. This means that the magnitude of Coriolis force disruptions of movement control seen in our experiments represent the largest to be expected in artificial gravity environments.

The first study we did was carried out without the subjects receiving any visual feedback about their reaching movements. We wanted to see how Coriolis forces would perturb movements in the absence of any possibility of visually mediated corrections of movement paths and termini. The experiment was conducted in total darkness except for the target-light which was visible to the subject until he/she lifted the finger from the start button to point to the target. Lifting the finger extinguished the target and initiated data collection by the video system. The target

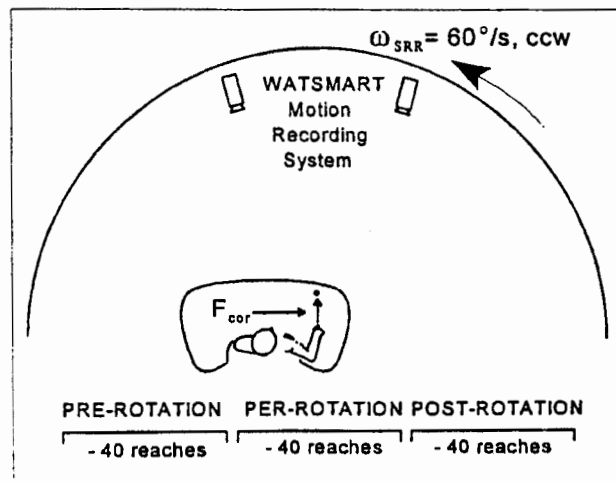


Figure 2 Illustration of the experimental situation and the experimental protocol.

board surface was completely smooth so the subject received neither visual nor direct tactile feedback about reaching accuracy.

Several features of the findings are notable. Firstly, the initial per-rotation measurements. movements show curved paths reflecting the action of the Coriolis forces and terminate far to the side of the target in the direction the Coriolis forces had acted. This means Coriolis forces deflect movement endpoints and is a disconfirmation of equilibrium point theories of movement control. Secondly, with repeated per-rotation reaches, movement paths become straighter and endpoints more accurate. After 15-20 movements, subjects are back to straight and accurate reaching movements despite the absence of visual and tactile feedback about reaching accuracy. Thirdly, the initial post-rotation reaches are mirror images (viewed from above) of the initial per-rotation reaches. This pattern of adaptation and aftereffect means that the nervous system is precisely anticipating the Coriolis forces and programming motor compensations for them.

A very important feature of the results is that during the first reaches during rotation the subjects feel the Coriolis force deviate their arm. However, with continued reaches the Coriolis force is no longer felt - although still present at the same magnitude - and the movements seem completely normal. During the initial post-rotation reaches the subjects report feeling something deviate their arm movements (leftward) despite the absence of any Coriolis force. What they sense as an external force deviating their arm is actually their own centrally generated compensation for the Coriolis forces associated with rotation - a compensation that is no longer appropriate. The important fact here is that continued exposure to the rotating environment feels - vis a vis limb movement control - completely natural and indistinguishable from the normal non-rotating environment.

Figure 3 shows averaged across subjects: the movement paths viewed from above of pre-rotation (baseline) reach, the initial and the final per-rotation reaches, and the initial post-rotation

reach. The adaptive patterns are obvious. Figure 4 presents the pattern of endpoint for all reaches in an experiment averaged across subjects.

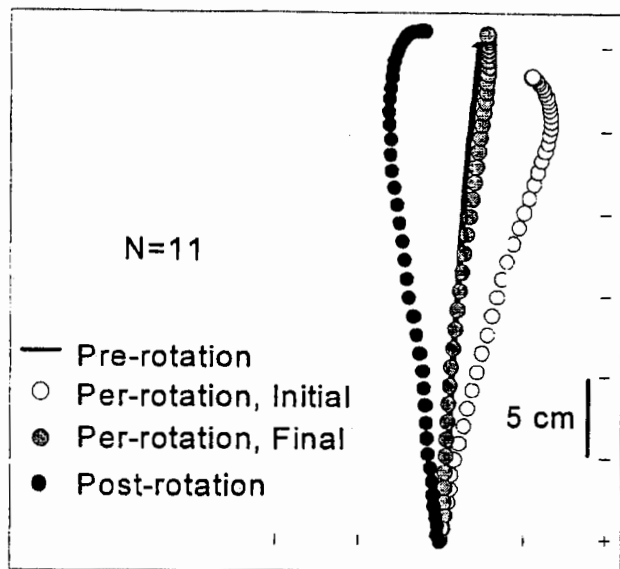


Figure 4

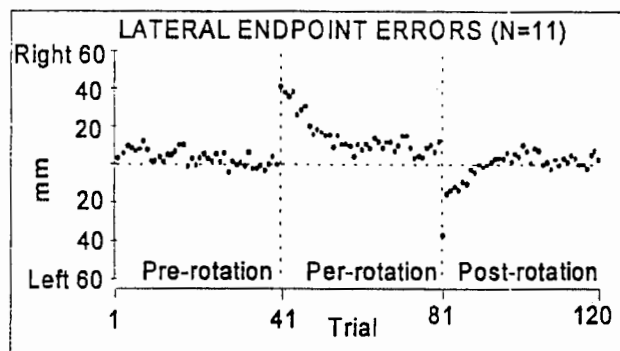


Figure 3

In other studies, we have allowed subjects full sight of their limbs during their pointing movements. In this case, subjects show the same initial per-rotation deviations of movement paths and endpoints, the errors are just as large. However, they adapt more rapidly. Within 8-10 movements they are again making straight reaches accurately to the targets!

We have recently begun testing subjects in the free fall phases of parabolic flight to see if adaptation to Coriolis forces would occur as it does under 1 g conditions. These subjects were also tested without receiving visual feedback

about reaching accuracy. They show patterns of movement deviation and adaptation that are similar to those seen in ground-based testing albeit initial movement errors so far appear somewhat smaller.

CONCLUSIONS

Contrary to earlier assumptions, limb movement control can be adapted quite easily to rotation rates as high as 10 rpm. Moreover, the rate of adaptation is remarkable rapid even in the absence of visual and tactile feedback about movement accuracy. When adaptation is complete, movements again seem completely normal and subjects no longer feel the Coriolis forces generated by their movements although they are still present. Their movements feel just like they do in a stationary environment. These findings mean that arm movement control can be adapted extraordinarily rapidly to rotation rates as high as 10 rpm. In other studies, we are finding similar adaptive modification of kicking movements made with the leg.

Previous research on the feasibility of using rotation as a means of generating artificial gravity focused on the disorienting and nauseogenic effects of head movements, including ones generated during locomotion. Up to now the conclusion has been that these problems place an upper bound of about 3 rpm on the rotational speeds that can be used, which will require a 100 meter radius to achieve 1 g. Whole body movements may be adaptable to much higher rates if we control the exposure by taking advantage of the capabilities we have demonstrated for rapid adaptation in motor subsystems.

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