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Head movements produced during linear translations in unexpected directions

E. T. Brown, H. Luan, M. J. Gdowski, and G. T. Gdowski, *Member, IEEE*

Abstract— **Passive translation of the body in space elicits a complex combination of directionally-specific torques that are exerted on the neck. The inertial torques that are produced by linear translation are counteracted by linear vestibular and proprioceptive reflexes that maintain head stability. A novel experimental apparatus was used in this study to translate human subjects in a random and unpredictable direction in order to quantify the head's 3-D movement with respect to the direction of translation. Head movements were found to be produced in systematic patterns as a function of stimulus direction. Roll and yaw head movements were produced in proportion to the magnitude of the lateral component of the translation. Pitch head movements were proportionate to the magnitude of the fore-aft component of the translation. One surprising observation was that head movements produced during lateral translations were, on average, 17% smaller than those produced during fore-aft translations. This suggests that linear vestibular reflexes that stabilize the head may be directionally-specific and more active during lateral whole body translations.**

I. Introduction

The cost of falls among older adults is staggering. In 2000, fall-related injuries exceeded $19 Billion [The Center for Disease Control and the National Center for Injury Prevention; 1, 2, 3]. During activities like walking, the central nervous system utilizes sensory feedback to maintain stability. Vestibular and proprioceptive signals are thought to be important in postural control [4-7]; especially in reflexively controlling the head's orientation [8-12].

When the vestibular system fails, both gait instability and an altered percept of body tilt occurs as a result of lateral motion [13]. These observations suggest that the vestibular system may have more of a role in maintaining the head's stability during lateral motions of the body than previously thought. One compelling reason for this role could be the biomechanics of the head/neck plant. When the head is oriented forward, the head's center of mass (COM) and moment of inertia are located superior and anterior to the rotational axis of the spinal column. Lateral motion of the body in this orientation results in torque exerted on the neck in two directions. One torque is in the direction of head roll about the anterior-posterior axis of the spinal column. The second torque is in the direction of head yaw about the vertical axis of the spinal column. The biomechanics are simplified during fore-aft translation in this orientation because the head's mass is symmetric about the midsagittal plane. In this case, torque is exerted only in the direction of pitch about the horizontal axis of the spinal column. Thus, we hypothesized that the head movements produced during linear body translation would depend upon the direction of translation in a manner consistent the biomechanical properties of the head/neck plant.

Prior studies in humans have quantified the head movement and neck muscle activation patterns during linear translation of the whole body in the fore-aft and side-to side directions [14-16]. However, the experimental apparatus used in those studies limited the experiments to specific and expected directions of translation. A novel experimental apparatus was used in this study to translate subjects in a random and unpredictable direction. This allowed us to quantify the head's movement with respect to the direction of translation.

Head movements were produced in systematic patterns as a function of stimulus direction that were consistent with the biomechanics of the head/neck plant. Roll and yaw head movements were produced proportionally with respect to the magnitude of the lateral component of the translation. Pitch head movements were produced proportionally with respect to the magnitude of the fore-aft component of the translation. One surprising observation was that the head movements produced during lateral translations were, on average, 17% smaller than those produced during fore-aft translations. This suggests that linear vestibular reflexes that function to stabilize the head may be directionally specific and more active during lateral whole body translations.

II. Methods

A. Study approval and subject consent

All procedures were approved by the Research Subjects Review Board under the direction of the Office for Human Subjects Protection at the University of Rochester. All participants provided informed consent prior to study procedures. All subjects were screened for hearing and vestibular disorders prior to participating in the study.

B. Subject preparation and experimental setup

3-D Head movements were recorded from subjects during experiments using a motion system (Vicon) that detected the locations of reflective markers that were placed on a swim cap worn by each subject. A Frankfort head coordinate system was defined by markers placed on the left and right auditory meatus. Another pair of markers was placed superior to the auditory meatus on the frontal plane to establish the vertical axis of the head coordinate system. The third axis was calculated offline as the cross product of the interaural and vertical axes, and the origin was defined as the midpoint of the interaural axis.

In all experiments, the subject was seated in a chair

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E. T. Brown is with the Dept. Biomed. Eng., Univ. Rochester, Eric_Brown@urmc.rochester.edu.

H. Luan and M. J. Gdowski are with the Dept Neuro. & Anat., Hongge_Luan@urmc.rochester.edu, Martha_Gdowski@urmc.rochester.edu

G. T. Gdowski is with the Dept. Biomedical Eng.,and Neuro. & Anat, Univ. Rochester, Rochester NY 14642 USA
Phone: 585-275-2580, fax: 585-756-5334, Greg.Gdowski@rochester.edu

upright along the earth vertical axis (Fig 1A). The apparatus was composed of two rotational motors and one sled/translational motor. The first rotational motor was located directly underneath the subject's chair. This motor was located on top of a sled that produced linear translation of the subject. The sled itself resided on top of a third base motor that rotated the entire apparatus about the earth-vertical axis. A five-point harness and vacuum packages were used to minimize upper torso movements.

C. Data acquisition

A National Instruments data acquisition system operating within a LabVIEW environment was used to control the sled/rotator apparatus. The real-time data collection system consisted of a PC and NI hardware (16-bit analog inputs and outputs, digital I/O lines and event clocks; 100μs). The PC was used to control the hardware and monitor data acquisition. A 3-D movement monitoring system (Vicon, Fig 1B) with six infrared cameras (910nm, 1280x1024 pixels) was used. All analog signals were sampled at 1kHz . Simultaneous kinematic marker data from at least 3 cameras was collected at 100Hz.

D. Experimental paradigm and data analysis

Subjects were translated in complete darkness in 24 different directions (0-360° in random 15° intervals, see Fig 1B). The direction of translation was manipulated by counter-rotating the base and chair rotators while the subject was positioned over both rotational axes (Fig 1A). In all cases, the subjects were stationary during sled positioning and were not able to predict the direction of translation. Once the sled was oriented, a trial (20-40s) was executed which consisted of a series of velocity trapezoids (peak velocity: 0.2m/s, peak acceleration: 0.25G, with a randomized step size of 5 or 10cm) that occurred randomly (normally distributed interval: 2.5±0.5s). The sled was then reoriented and trials were repeated for all translation directions. The following conventions were used for direction of translation: 0°-rightward, 90°-forward, 180°-leftward, and 270°-backward.

Head movement kinematics were calculated offline using a model generated within the Vicon software (IQ and BodyBuilder). Pitch, roll, and yaw were defined as angular head in space rotation about the Frankfort plane. In these experiments, head rotation in space was equivalent to head on trunk rotation. The magnitude of angular head velocity was calculated as the square root of the sum of squared angular velocity components. Matlab software was used to align and average the response to individual random perturbations with respect to the stimulus onset (Fig 2). All reported values are the mean for all subjects. T-tests with an alpha of 0.05 were performed to compare subject and population mean differences for statistical significance.

III. Results

Rotational head movements were always elicited when the body was translated in space, *regardless of the direction of translation*. The magnitude of the head rotation was evaluated as a function of the direction of translation. Fig 3 is a polar plot relating the peak mean angular head velocity to the direction of translation. Responses during side-to-side

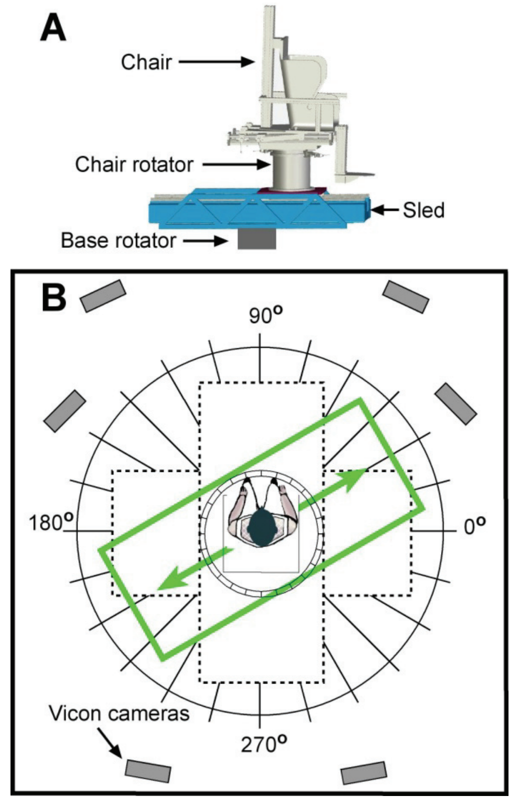

Fig 1. **A.** Side-view of the apparatus including: 1) chair, 2) chair rotator, 3) sled, and 4) base rotator. **B.** Top-down schematic of the subject's orientation with respect to the sled. Translation in a direction of 30° is highlighted (*green*). Subjects were translated in all indicated directions of translation (15° increments).

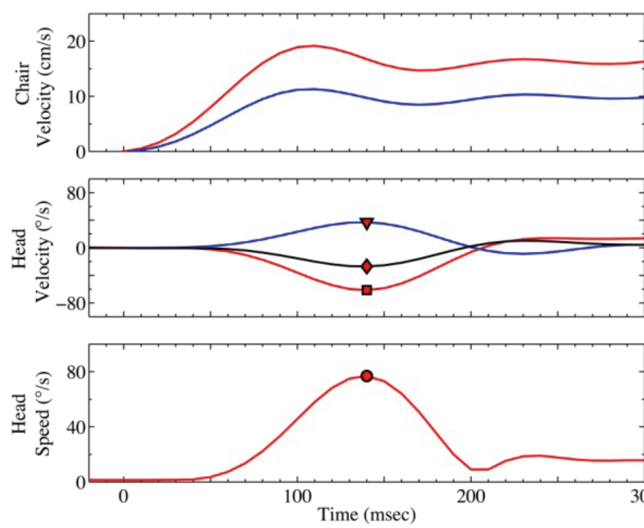

Fig 2. Typical response to a trapezoidal perturbation in a direction of 30° (*green*, **B**). **Top**: fore-aft (*blue*) and side-to-side (*red*) sled movements for a single trapezoid. **Middle**: head movement kinematic components (pitch: *blue*, roll: *red*, and yaw: *black*). **Bottom**: head movement magnitude. Peak responses for head movement components and magnitude are indicated with symbols.

translations tended to be smaller than those during fore-aft translations (p=0.035). This resulted in a slightly elliptical pattern in Fig 3. A ratio of the fore-aft/side-side dimensions of the plot was 1.17 for the subject population, indicating that the head movement kinematics were on average 17% smaller during lateral translations.

A. Directional components of head movements as a function of stimulus direction

The goal of this study was to characterize and quantify head movements during combined fore-aft and lateral translation. The largest rotational pitch head movements were observed during fore-aft translation (73 º/s at 90º translation, Fig 4A). However, pitch head movements were observed for most directions of translation, where the amplitude increased in proportion to the amount of translation in the fore-aft direction. Similarly, the largest rotational roll head movements were observed during lateral translation (59 º/s at 0º translation, Fig 4B). However, these head movements were typically smaller than pitch head movements that were observed during fore-aft translation ($p<0.003$). Roll head movements were observed for most directions of translation, with an amplitude proportional to the amount of translation in the lateral direction.

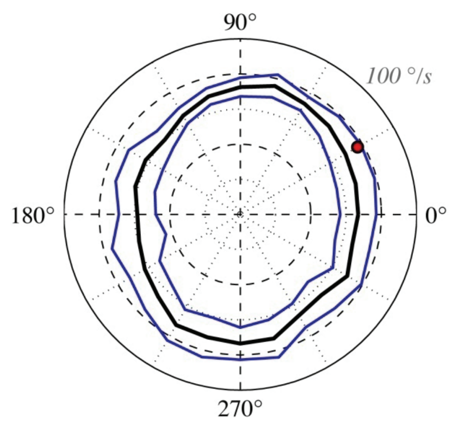

Fig 3. Mean of peak head speed for four subjects during whole body translation as a function of translation direction. Blue lines indicate standard error. Filled circle is the response of a typical subject during 30° translations (Fig 2).

B. Yaw head movements produced during linear translation

Yaw head movements were commonly observed during linear translations. They were significantly smaller ($p<0.05$) than roll (3/4 subjects) and pitch (4/4 subjects) head movements that were produced (Fig 4C). Like other head movement components, they exhibited amplitude characteristics that depended upon the direction of translation. Yaw head movements were maximally produced during lateral translations and were almost non-existent during fore-aft translations.

IV. Conclusions

We hypothesized that head movements would be produced during whole body translation as a consequence of the location of the head's center of mass with respect to the spinal column. The largest yaw head movements were produced during lateral linear translations, consistent with the head's center of mass producing the largest torque on the neck in this direction.

To our knowledge, this is the first study in which 3-D head movements were systematically characterized and quantified as a function of the direction of whole body translations. Unlike prior studies [14-16], the subjects had no knowledge of the direction of translation that would be experienced. A surprising outcome of these experiments was that head movements produced during lateral translations were smaller than the head movements produced during fore-aft translations. Several factors could explain this directional specific relationship between head movement kinematics and translation. The stiffness and viscosity of the neck musculature could be different for roll movement compared to pitch movement. Such differences might also explain why head movements are larger during fore-aft translations. There could also be differences in reflexive mechanisms that function to stabilize the head during translation that are dependent upon the direction of translation.

The vestibular endorgans are capable of encoding information about linear translation in any direction [17-19]. This ability is not preserved centrally. Neurons located in the lateral vestibular nuclei, which include those projecting to the cervical spinal cord, are sensitive to the direction of

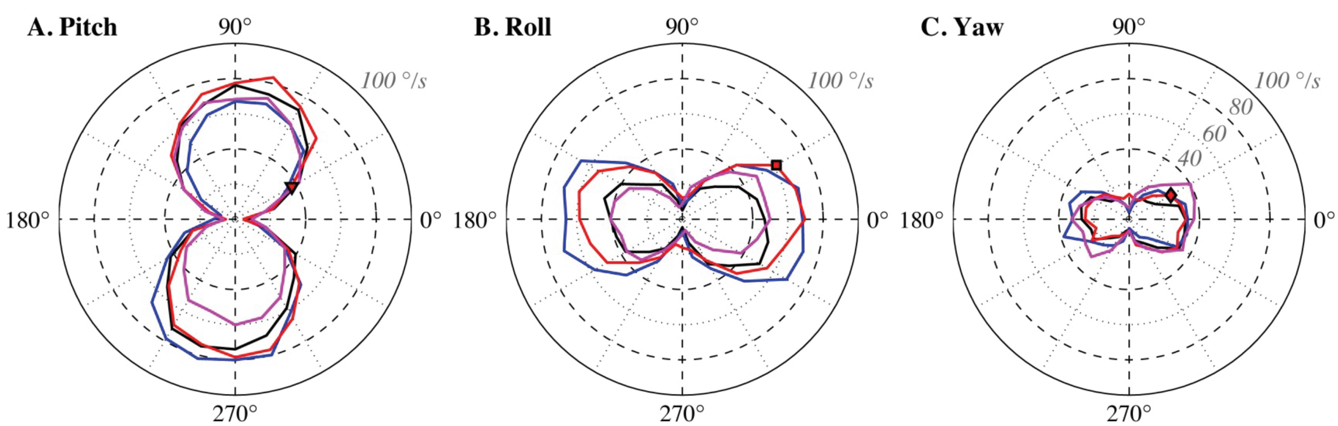

Fig 4. Head movement components produced during whole body translation (0.25G, 0.2 m/s peak velocity) for four subjects as a function of the direction of translation. Shown are mean peak rotational head velocity in **A)** pitch, **B)** Roll, and **C)** Yaw. Colors denote each subject. Symbols are the response of a single subject during 30° translations (Fig 2).

translation. However, the majority of these neurons are sensitive in directions that are within 45º of pure lateral motion [20]. Relatively few are sensitive to fore-aft translation, and those that are have fairly low gains or sensitivity [21]. Such differences suggest that if linear vestibulocollic reflexes are more active during side-side lateral translations, they function to reduce head rotation. We did not quantify the neck EMG activity produced during linear translations and therefore could not ascribe specific response attributes to reflexive activation of the neck muscles. However, other studies [14-16] have shown the reflexes to be active during similar conditions, suggesting that vestibular reflexes did contribute to the responses we observed.

It is interesting to note that rotational head movements are produced during linear translation, which likely activates the semi-circular canals. Consequently, the rotational vestibulocollic reflexes that derive input from the semi-circular canals were also likely evoked. The rotational reflexes function to produce compensatory responses with respect to the vestibular signal. Interestingly, in this case the vestibular signal is produced by the head movement caused by the linear translation. Thus, these reflexes could also function to reduce head-on-trunk rotations produced during linear translation. Work in progress will determine how vestibular reflexes contribute to the observed head kinematics.

V. Acknowledgements

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VI. References

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