Evaluating Eye–Body Coordination During Unrestrained Functional Activity in Older Persons

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Background. Traditional paradigms for the study of ocular-motor control restrain subject motion and have not adequately quantified the sensorimotor strategies used by older persons to control gaze while performing activities of daily living. The purpose of our study was to describe eye–head–trunk coordination during a functional activity in freely moving community-dwelling older persons.

Methods. Thirty-five community-dwelling older persons (age range 71–92 years) participated in this study. Surface electro-oculography was used with an electromagnetic tracking device to measure vertical eye movement and linear and angular head position while each subject performed a stand-from-chair task.

Results. Standing from a chair involved low-frequency head motion (median $z$ = 0.25 Hz; median pitch = 0.32 Hz). The distribution of phase for eyes versus vertical body motion were skewed toward head–trunk leading, suggesting that eye motion follows vertical body motion. Vertical gaze, however, was in phase with and moved in the same direction as head pitch.

Conclusions. Gaze (eye position in space) was an active, integrated component of the standing motion. The results imply that both the oculomotor system and the head motor system in older persons are coordinated to direct gaze and, when necessary, work to suppress the vestibuloocular reflex. The interaction of eye–head–trunk motion provides a basis for understanding how a breakdown in the gaze control mechanisms in older persons might contribute to the risk of falling and fall-related injuries.

Healthy older persons have deficits in the gain and phase of the vestibulo-ocular reflex (1), in visual target localization (2), and in smooth pursuit (3) as a consequence of aging. These “natural” deficits may cause oscillopsia and contribute to the gait and balance impairments that have been identified as risk factors for falling and serious injury in community-dwelling older persons (4). The specific sensori-motor strategies that elders use to coordinate eye and body motion to adapt to deficient oculomotor reflexes are not known because there has not been a systematic evaluation of these strategies while elders perform routine activities of daily living (ADL).

Several researchers have proposed that postural control is regulated by a “proprioceptive linkage” between the neural commands controlling eye motion and stabilization of the head, trunk, and lower extremities (5). The interaction between saccades, the vestibulo-ocular reflexes, and the mechanisms responsible for eye–head coordination has been studied extensively [reviewed by Goossens and Opstal (6)], but the paradigms used to evaluate these mechanisms involve constraining the subject’s head or body motion (5,6) or strictly controlling the visual environment in a laboratory setting so that the localization of specific visual targets can be assessed (7). The purpose of our study was to evaluate the control of gaze, eye–head, and eye–trunk coordination in freely moving older persons who were performing a stand-from-chair task.

Methods

Subjects

Thirty-five older individuals (26 women and nine men; 81 ± 5 years of age [mean ± SD]) residing in assisted living facilities or senior apartments in the Minneapolis, Minnesota area volunteered to participate in this study. All subjects provided written informed consent, and the protocol for the project was approved by the University of Minnesota Institutional Review Board. Each subject passed a screening examination and was able to walk independently for short distances, had visual acuity of at least 20/70, and was cognitively intact (Folstein Mini Mental score > 23) (8). None of the subjects had artificial limbs or severe medical conditions that would limit mild exercise.

Task

The natural motion of standing from a chair was evaluated, and subjects were free to use any movement strategy they wished to achieve stance. There were no instructions concerning the direction of looking, and subjects were not asked to fixate on a visual target. None of the subjects reported symptoms of oscillopsia during the test. The same chair was used with all subjects, and the subjects were not restrained in any way. For safety reasons, however, each subject wore a belt to provide a grab surface for researchers standing nearby in case the subject began to fall. All subjects were tested at their place of residence.

Procedures

Eye movements were recorded using standard electrooculography (EOG) with Ag-AgCl surface electrodes 4 mm in diameter (reference electrodes on the forehead) (9). Signals were processed with a bandpass filter (0.05–30 Hz). Each subject wore a firmly fitted headband with a 6 degree-of-freedom electromagnetic sensor (Polhemus, Colchester, VT).
mounted at the top of the band. A second sensor was fixed to the back of the subject at the level of the first thoracic spinous process. The alignment reference frame of the head and trunk sensors were relative to a transmitter fixed in space approximately 75 cm from the subject on a nonmetallic frame.

EOG and body position recordings were sampled at 120 Hz and 60 Hz, respectively, to prevent signal aliasing. EOG signals were calibrated statically to reflect degrees of eye motion (10). The aggregate data set (EOG plus head and trunk position) was reprocessed using a zero phase shift Butterworth (MathWorks, Inc., Natick, MA) digital low-pass filter with a 30-Hz cut-off frequency to preserve a 0.05- to 30-Hz bandwidth [the minimum recommended by Juhola (11)] for all data channels. Data were resampled to a common frequency of 60 Hz, and a cross-correlation function (12) was applied to the resampled data to calculate the phase of vertical eye versus head or trunk motion in seconds of lead or lag. By our convention, eye and head or trunk movements are in phase at 0 seconds. Eyes lead the head or trunk when the phase is positive, whereas eyes lag the head or trunk when the phase is negative.

Data Processing and Analysis

Spurious data of individual artifacts in the EOG recordings were replaced by values generated by an interpolation technique computed by the Matlab function "spline.m" (MathWorks, Inc., Natick, MA). The interpolating function was constructed from the data before and after the occurrence of the artifact and was based on a cubic spline (13). The spline was applied by the researchers to remove blink artifact and saccades while attempting to leave any underlying smooth eye motion intact.

Linear and angular head and trunk motions were measured during the standing task (Figure 1). Vertical gaze (single dimension) was described to calculate the position of the eyes-in-space (defined as the sum of head pitch in space and vertical eye motion in the head). Vertical eye motion and gaze were evaluated against head motions using the cross-correlation analysis described above. One-way Kruskal-Wallis (nonparametric) analysis of variance (ANOVA) or a parametric ANOVA (for normally distributed data) were used to determine if there were statistically significant changes in the maximum covariance, in the phase of eye–body segment displacement, or in the predominant frequency of vertical eye motion with and without the application of cubic spline interpolation.

RESULTS

Head Motion and Gaze

Standing from a chair involved low frequency head motion (median $z = 0.25$ Hz; median pitch $= 0.32$ Hz), and the mode of movement was primarily in the vertical plane (Figure 1). The mean ($\pm SD$) peak-to-peak head motion in yaw, pitch, and roll was $16^\circ + 14^\circ$, $33^\circ + 15^\circ$, and $10^\circ + 11^\circ$, respectively. Head pitch and gaze were in phase (median phase $= 0$ seconds for spline and no-spline conditions; interquartile range $-0.20$ to 0.32 seconds), and the inspection of individual records indicated a coordination of gaze

and head control during the standing activity (Figure 1). Specifically, as gaze moved downward to prepare for standing, the head also rotated downward. As gaze rotated upward to search the visual environment while rising from the chair, the head also pitched upward (Figure 1).

Eye Motion Versus Head Motion

The median phase was 0 seconds for head and trunk $z$ displacement versus vertical eye motion regardless of the application of spline, but the distribution of phase values was toward the negative (eyes lag head; Figures 2A and 2B). For head and trunk pitch versus vertical eye motion, the distribution of phase values was uniformly distributed around a point on the time axis just slightly above 0 seconds (Figures 2C and 2D; median phase for no-spline and spline: 0.04 and 0.18 seconds for head pitch-vertical eye, respectively, and 0.26 and 0.25 seconds for trunk pitch-vertical eye, respectively).

Influence of EOG Processing on Maximum Covariance and Predominant Frequency

The maximum covariance for head pitch versus vertical gaze increased significantly when cubic spline was applied (from a mean of $r = .67$ to $r = .75$, $F_{1,68} = 4.03$, $p = .048$; 95% confidence interval [CI] 0.70–0.79). Cubic spline interpolation also improved the maximum covariance of vertical eye motion versus head and trunk linear and angular motion. The 95% CI for maximum covariance shifted upward (toward stronger correlation intervals) in each case that the cubic spline was applied. This shift in maximum covariance is illustrated in the scatter plots of phase versus maximum covariance where the density of the scatter is clustered at the top of each plot for spline-processed data (Figure 2). The range of the predominant frequency of vertical eye motion was from 0.21 to 0.31 Hz without spline and from 0.25 to 0.32 Hz with spline. There were no statistically signifi-
cant changes in the frequency spectrum of vertical eye movement between cubic spline and nonspline processed trials.

**DISCUSSION**

Our findings provide the basis for evaluating eye, head, and trunk coordination during activities that have the potential to create risk for falling in older persons. Therefore, our method has an advantage over head-fixed or body-restrained techniques for evaluating oculomotor control. Whereas eye–head coordination is primarily a subcortical process, the head movement component of gaze shift is open to voluntary control (14). This means that the mechanisms that create oscillopsia in older persons (i.e., the separate contributions of eye and head movement to the stabilization of gaze) can be assessed in a relevant environment as elders attempt to perform an activity of daily living without restricting their natural, full body motion.

The purpose of the vestibuloocular reflex (VOR) is to fix gaze while the head is in motion by counter-rotating the eyes with respect to the head. We found that vertical eye motion tended to lag vertical linear body motion (Figures 2A and 2B), but gaze was in phase (Figure 2, inset) and shifted in the same direction as head pitch (Figure 1). The mechanism that controls gaze appeared to suppress the vertical VOR so that the eyes could move with the head. Therefore, in our subjects gaze was an active, integrated component of the standing motion with frequent shifts that paralleled head pitch. In addition, it was not likely that horizontal or torsional VOR played a major role in the patterns that we observed, because head yaw and roll were relatively small components of the overall head motion compared with pitch (Figure 1, bottom traces).

Our findings support the notion that both the oculomotor system and the head motor system are controlled by the same internally generated motor-error signal (15) because the head and gaze move in phase and in the same direction, but this theory might apply only to conditions where the head and eyes are initially aligned (6). The interaction of eye, head, and trunk movement might indicate how a breakdown in the gaze control mechanism contributes to the risk of falling and fall-related injuries.

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