Residual Torsion Following Ocular Counterroll

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ABSTRACT: **A recent study on static ocular counterroll suggested the existence of residual torsion (RT): when healthy subjects repositioned their head to the upright position after sustained static tilt, eye position differed from the original ocular torsion measured prior to the static head tilt. Our experiments aimed at further characterizing this phenomenon. Using a three-dimensional motorized turntable, healthy human subjects *(n* = 8) were rotated quasi-statically (0.05 deg/s^2, 2 deg/s velocity plateau reached after 40 s) from the upright position about the naso-occipital axis. Three full whole-body rotations were completed while subjects fixed upon a blinking laser dot straight ahead in otherwise complete darkness. Three-dimensional eye movements were recorded with modified dual search coils (wires exiting inferiorly). Torsional position of the right eye at consecutive upright body positions was analyzed. The torsional eye position before the beginning of the chair rotation was defined as zero torsion. On average, the right eye was intorted by 1.3° or extorted by 2.0° after the first full chair rotation in the clockwise or counterclockwise direction, respectively. These torsional offset values of the right eye did not significantly change after the two subsequent full chair rotations. We conclude that RT observed after static ocular counterroll is the result of static hysteresis, that is, a position lag of the eye, which depends on the direction of head roll. The fact that residual torsion did not further increase after the first rotation cycle emphasizes that RT is a static rather than a dynamic phenomenon.**

KEYWORDS: **vestibulo-ocular reflex; head roll; head tilt; otolith; eye movements**

INTRODUCTION

Tilting the head in the frontal plane, so-called head roll, leads to counterrotational movements of both eyes in the opposite direction. This ocular counterroll is a result of the torsional vestibulo-ocular reflex (tVOR) that serves to stabilize torsional eye position in space. In the static condition, that is, during sustained head roll, the otolith organs that sense the directional change of the gravitational force vector with respect to the head predominantly mediate the tVOR. In humans, torsional eye position compensates only about 10 to 20% of static head roll,[1–4] with large interindividual differences.[5] In the dynamic condition, during head or whole-body oscillation

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about the earth-horizontal naso-occipital axis, the combined semicircular canal and otolith stimulation leads to a torsional velocity that reaches up to 60% of the torsional head velocity,[1] whereby the otolith contribution to the gain of the tVOR is around 10% of the head velocity.[6,7]

Static ocular counterroll is sustained during fixations, saccades, and smooth pursuit eye movements in primary, secondary, and tertiary positions.[8–10] Therefore, the plane to which all eye positions are confined, the so-called Listing's plane,[11,12] is simply shifted along the torsional axis of the head-fixed coordinate system.[9]

Recently, Schworm *et al.* reported an interesting finding in static counterroll,[3] examining ocular torsion in response to consecutive head roll positions of 0°, 15°, 30°, and 45° to the right or left as measured by three-dimensional video oculography. Each head position was held for 10 s. After head reorientation from the 45° roll to the upright position, the eyes did not completely rotate back to the initial torsional position, but settled at a torsional offset position in the direction of the previous counterroll. This finding is surprising because torsional eye position is assumed to result directly from the input of the otolith organs that sense the direction of the gravitational force vector with respect to the head. The direction of this vector was identical before and after static head roll. Therefore, factors other than actual head position must determine torsional eye position when the head is moved back to upright after a head roll.

Our study was motivated by this unexpected phenomenon, which we call residual torsion (RT). Using modified dual search coils (wires exiting inferiorly to prevent torsional artifacts by the lids) and a motorized turntable (whole-body roll rotation to prevent ocular motor changes by neck proprioception) we first sought to confirm the existence of RT in healthy human subjects. By very slow (i.e., quasi-stationary), continuous chair rotations, abrupt displacements between static roll positions were prevented to exclude dynamic influences of chair movement on residual torsion. Finally, by completing three full chair rotations, we were able to further characterize the critical parameters that determine residual torsion.

MATERIALS AND METHODS

Subjects

Eight healthy human subjects (4 male, 4 female; 30 to 42 years old) participated in this study. Informed consent was obtained after full explanation of the experimental procedure. The protocol was approved by a local ethics committee and was in accordance with the ethical standards of the 1964 Declaration of Helsinki for research involving human subjects.

Experimental Setup

Subjects were seated upright on a turntable with three servo-controlled motor driven axes (prototype built by Acutronic, Jona, Switzerland). The head was restrained with an individually molded thermoplastic mask (Sinmed BV, Reeuwijk, The Netherlands). Subjects were positioned so that the center of the interaural line was at the intersection of the three axes of the turntable. Pillows and safety belts minimized movements of the body. The head was surrounded by an aluminum coil frame (side length 0.5 m). The coil frame generated three orthogonal digitally synchronized magnetic wave field signals of 80, 96, and 120 kHz. A digital signal processor computed a fast Fourier transform in real time on the digitized search coil signal to determine the voltage induced on the coil by each magnetic field (system by Primelec, Regensdorf, Switzerland). Coil orientation could be determined with an error of less than 7% over a range of ±30° and with a noise level of less than 0.05° (root mean squared deviation).

Eye- and Head-Movement Recording

Three-dimensional eye movements were recorded binocularly with dual scleral search coils (Skalar Instruments, Delft, The Netherlands). In this study only data from the right eye were analyzed. Search coil annuli were calibrated with a method described previously.[13] After local anesthesia of the conjunctiva and cornea with oxybuprocaine 0.4%, search coils were placed around the cornea. To minimize torsional artifacts by mechanical interaction of the upper eyelids touching the nasally exiting wire of the coils and thus leading to annulus rotation, modified search coils with the wire exiting inferiorly (at 6 o'clock) were used.[14] Eye, head, and chair position signals were digitized at 1000 Hz per channel with 16-bit resolution, and stored on a computer hard disk for off-line processing.

Experimental Protocol

Subjects were rotated on a three-dimensional turntable from the upright position about the earth-horizontal naso-occipital axis clockwise or counterclockwise at a constant angular velocity of 2 deg/s. To reach this velocity plateau from the initial upright position, the chair was accelerated by 0.05 deg/s^2, which is below the stimulation threshold of the semicircular canals.[15,16] The velocity plateau was reached after 40 s. A total of three consecutive 360° chair rotations were performed before the chair was stopped.

A space-fixed laser dot was projected straight ahead onto a spherical screen at a distance of 1.4 m in front of the subject's eyes. Every 2 s, the laser dot was turned on for a duration of 20 ms. Subjects were instructed to look at the laser dot and to keep their eyes at this position during the off-periods. The short duration of on-periods ensured that the smooth pursuit system was not activated. Experiments were performed in otherwise total darkness.

Data Analysis

Search coil signals from the right eye were processed with interactive programs written in Matlab Version 6.5. Three-dimensional eye positions of the right eye were computed as rotation vectors.[17] The sign of the torsional component of a rotation vector is determined by the right-hand rule so that clockwise torsion, as seen by the subject, is positive and starts with right-ear-down from upright. For convenience, torsional eye position was converted to degrees (°).

For statistical analysis, the torsional position of the right eye (E) was determined at four different instances when the body was in the upright position: before chair rotation (E_0), and after each of the three consecutive full chair rotations when the chair crossed the upright position (E_1, E_2, E_3). By definition, $E_0 = 0$, as this torsional position of the right eye was taken as reference. E_1, E_2, and E_3 were determined by fitting a sine function with two harmonics and an offset through torsional eye positions as a function of torsional chair position 180° before and 180° after the upright position. The value of the fitted curve at the upright chair position (i.e., E_1, E_2, and E_3) represented residual torsion.

RESULTS

FIGURE 1 shows calibrated torsional eye position of the right eye plotted against torsional chair position in a healthy subject (A.P.). Starting from the upright position, a total of three 360° chair rotations about the earth-horizontal naso-occipital axis were performed in both directions. For reference, zero ocular torsion was determined

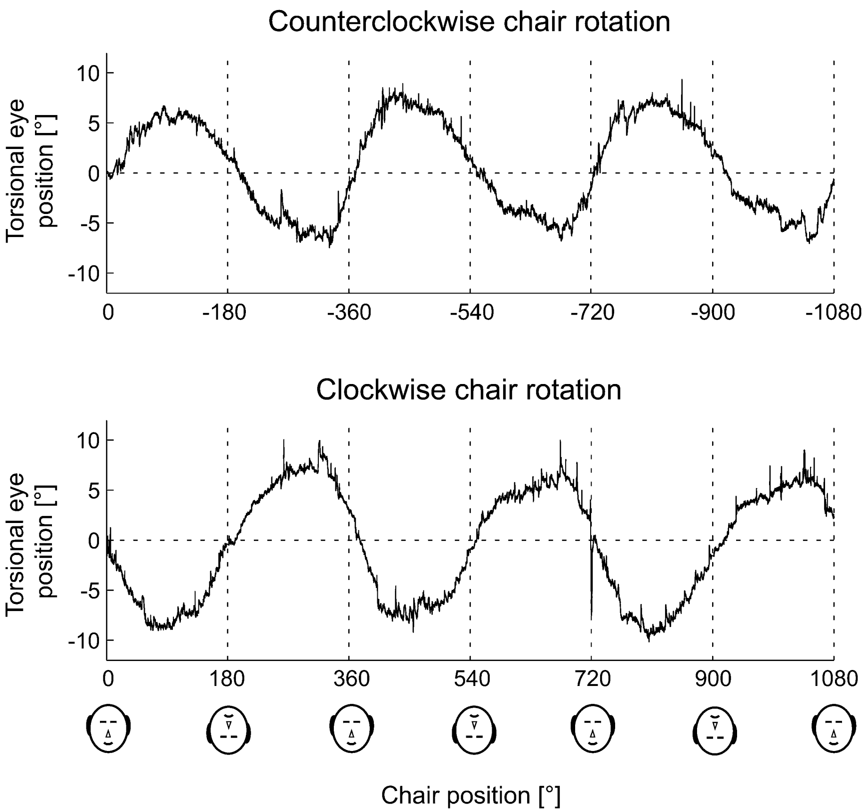

FIGURE 1. Example of calibrated torsional eye position (magnetic search-coil data, 1000 Hz) in a healthy subject (A.P.) during three 360° constant velocity turntable rotations in the roll plane from upright (velocity: 2 deg/s; acceleration before the velocity plateau: 0.05 deg/s^2). **Upper Panel**: counterclockwise chair rotation. **Lower Panel**: clockwise chair rotation. Clockwise eye torsion, as seen by the subject, is positive.

immediately before the chair started to move (see METHODS). After the first full counterclockwise chair rotation (i.e., rotation starting with the left ear moving down; FIG. 1, upper panel), the right eye was still in an intorsional position and had not completely returned to zero torsion. Likewise, after the first full clockwise rotation (i.e., rotation starting with the right ear moving down; FIG. 1, lower panel), the right eye was still in an extorsional position, despite the upright chair position. These residual torsional positions with the chair upright remained similar after the second and third consecutive full chair rotations in either direction (intorsional after counterclockwise chair rotations, extorsional after clockwise chair rotations).

FIGURE 2 summarizes the torsional positions of the right eye in all eight healthy subjects. Consistently, after the first full chair rotation, average torsional position (±1 SD) of the right eye in the upright body position was negative (= intorsion) when the direction of the chair movement was counterclockwise (FIG. 2, upper panel) and positive (= extorsion) when the direction chair movement was clockwise (FIG. 2,

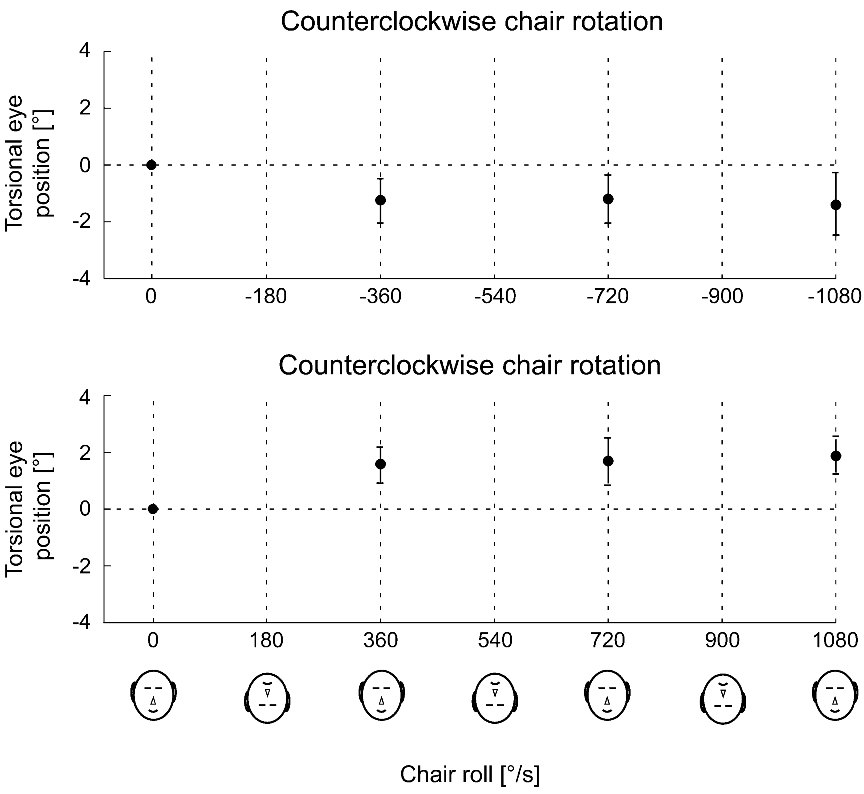

FIGURE 2. Average torsional eye position (±1 SD) of the right eye in all healthy subjects *(n* = 8) at upright body position. **Upper Panel**: counterclockwise chair rotation. **Lower Panel**: clockwise chair rotation. For reference, torsional eye position at starting upright body position was set to zero. Clockwise eye torsion, as seen by the subject, is positive.

lower panel). Both average torsional positions after the first rotation were statistically significant from zero (paired *t*-test, $P < .01$). The two consecutive rotations, however, did not further change the amount of residual torsion (ANOVA among the data obtained after the first, second, and third rotation, $P > .1$).

DISCUSSION

The present study investigated RT observed after static ocular counterroll when healthy subjects were reoriented back to the upright body position. In eight healthy human subjects, three consecutive 360° whole-body rotations about the naso-occipital axis were performed. To eliminate dynamic contributions to the torsional vestibulo-ocular reflex (tVOR), the acceleration level was below the threshold of the semicircular canals, and the subsequent velocity plateau was low (2 deg/s), that is, quasi-stationary.

After the first 360° roll chair rotation, torsional eye position in the upright body position differed from the torsional eye position determined at the beginning of the chair rotation. This difference represents RT. After counterclockwise chair rotation there was consistent residual intorsion, and after clockwise chair rotation consistent residual extorsion. The subsequent second and third 360° rotations did not further change the amount of RT. Thus, the first 360° rotation determined the direction-specific torsional offset that remained valid for the subsequent rotations.

Our results corroborate the recent findings of Schworm *et al.* on RT after head roll reorientation back to the upright position.[3] To our knowledge, Schworm *et al.* were the first to notice the existence of RT, although many previous studies analyzed ocular counterroll in great detail.[1,9,18,19] Using dual search coils to measure torsional eye position evoked by static head roll, Collewijn *et al.* regularly recorded ocular torsion in upright position coming back from different roll positions.[1] In contrast to the study of Schworm *et al.*, the torsional position with the head upright scattered around the original torsional position in a range of about ±1°. Possibly, the maximal head roll tilt of ±20° was too small to identify RT in the torsional background noise, while Schworm *et al.* rolled the head up to 45°.

The results by Schorm *et al.*[3] did not allow distinction between two different hypotheses on the origin of RT. Either RT is a result of the displacement between the different static head roll positions (dynamic hypothesis) or it represents a torsional lag of the eye, which depends solely on the previous orientation of the head with respect to gravity (static hypothesis). Our experiments clarified this issue, as RT was still present without dynamic displacements between static roll positions. Using quasi-static and continuous rotation about the naso-occipital axis, consistent RT could be elicited. Of course, it would be desirable to rotate the chair even more slowly, but velocities lower than 1 deg/s are not tolerable for human subjects, as in this case the full heel-over-head rotation takes longer than six minutes.

In conclusion, our results indicate that RT represents a lag of eye torsion as a function of head roll and thus is a biological example of static hysteresis. What could be its mechanism? At this point, we can only speculate on possible locations within the structures of the tVOR where static hysteresis might occur. Possible candidates are the otolith organs, the ocular motor plant, or the torsional integrator in the brainstem. Another question related to the problem of residual torsion is how to define zero ocular torsion for reference. As we have shown, this definition is rather arbitrary and depends on previous head roll.

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