

# Three-Dimensional Hess Screen Test with Binocular Dual Search Coils in a Three-Field Magnetic System

Oliver Bergamin,<sup>1</sup> David S. Zee,<sup>2</sup> Dale C. Roberts,<sup>2</sup> Klara Landau,<sup>3</sup> Adrian G. Lasker,<sup>2</sup> and Dominik Straumann<sup>1</sup>

**PURPOSE.** To establish an objective Hess screen test that allows a simultaneous and binocular analysis of all three axes of eye rotation.

**METHODS.** In orthotropic and strabismic human subjects, both eyes were recorded with dual scleral search coils in a three-field magnetic system. Before mounting the search coil annuli on the eyes, the voltage offsets of each channel and the relative magnitudes of the three magnetic fields were determined. For calibration, subjects were only required to fix monocularly on a single reference target. During fixation of targets on the Hess screen by the uncovered eye, the three-dimensional eye position of both the occluded and the viewing eye was simultaneously measured.

**RESULTS.** For clinical interpretation, an easy to understand graphical description of the three-dimensional Hess screen test was developed. Positions of orthotropic and strabismic eyes tended to follow Listing's law, which in both eyes allowed the determination of the primary position, that is, the position of gaze from which pure horizontal and pure vertical movements do not lead to an ocular rotation about the line-of-sight. To a first approximation, the location of primary position is a result of the summation of the individual rotation axes of the six extraocular muscles and thus can be used to infer which muscle is paretic.

**CONCLUSIONS.** The three-dimensional Hess screen test with binocular dual search coils in a three-field magnetic system is an objective method to assess the ocular alignment in three dimensions with high precision. From these recordings, the clinician can relate deviations of primary position to specific eye muscle palsies. (*Invest Ophthalmol Vis Sci.* 2001;42:660-667)

The conventional Hess screen test<sup>1</sup> provides a concise description of the two-dimensional (vertical and horizontal) position of both eyes in the absence of fusional constraints. The Hess screen consists of a red grid printed onto a gray tangent screen, usually located at a distance of 0.5 m from the subject. A red filter is placed in front of one eye and a green filter in front of the other eye. The eye with the red glass fixes on standard locations on the grid, which cannot be seen by the eye with the green glass. The latter eye, however, guides the pointing of a green light by the patient, which cannot be seen

by the eye with the red glass. The green light is moved by the patient to the location on the grid. The horizontal and vertical difference between the locations of the green light and the standard positions on the red grid corresponds to the phoria, the ocular misalignment in the absence of fusion. This procedure allows one to distinguish between concomitant and incomitant strabismus.<sup>2</sup> In the case of eye muscle palsy, the paretic muscle can be identified easily. Prerequisites of an accurate Hess screen test are sufficient binocular visual acuity and the ability to fix steadily on the targets.

The two-dimensional Hess screen test is not an objective method, because the patient has to indicate the position of the green light. Another disadvantage is that the torsional degree of freedom of eye rotation cannot be measured easily. This makes it impossible to test whether the ocular motor laws for three-dimensional eye position<sup>3-5</sup> are valid in strabismic eyes.

Objective measures of torsional eye position are based on ophthalmoscopy<sup>6</sup> and fundus photography.<sup>7</sup> Here, the lines between the centers of the optic disc and the fovea are determined. In orthotropic subjects, this line is not horizontal, because the optic disc is higher than the fovea, a configuration that is named excyclorotation. Perimetry of the blind spot (scotometry) also allows one to quantify the cyclorotation of the fundus, but this procedure requires excellent cooperation by the patient. Both fundus photography and scotometry are usually restricted to an eye position with the line-of-sight pointing straight ahead. If the clinician wants to determine ocular torsion at different horizontal, vertical, and oblique directions of gaze, no objective measures of ocular torsion are available.

Methods that allow the description of relative torsion between both eyes with the line-of-sight pointing straight ahead include the Maddox double-rod test and the Bagolini striated lenses.<sup>8</sup> Using the synoptophore,<sup>9</sup> the Harms tangent scale,<sup>10</sup> or the Lancaster test with horizontal or vertical bars,<sup>11</sup> one can measure the torsional deviation between both eyes at different gaze directions. Afterimages can be used to describe the relative rotation of the eyeball about the visual axis at different directions of gaze with respect to the ocular position where the vertical or horizontal light bar was flashed.<sup>12</sup>

An ideal Hess screen test should not only give the difference in torsion between the two eyes, but also the torsion of each eye separately and simultaneously at any direction of gaze. Furthermore, this test should be objective, that is, not rely on a subjective alignment of visual bars. The dual search coil technique meets all these requirements. This method, developed by D. A. Robinson in the early 1960s, was the first that could objectively measure all three rotatory components of ocular movements.<sup>13</sup> In the mid-1980s, H. Collewijn<sup>14-16</sup> modified the scleral annulus, such that three-dimensional search-coil measurements could be applied in humans routinely.

The aim of this article is to provide an algorithm for the neuro-ophthalmologist and strabismologist on how to combine the conventional Hess screen test with binocular three-dimensional search coil measurements and analyze the data for clinical purposes.

The advantage of the method will be demonstrated with examples of an orthotropic and a strabismic subject, as well as

---

From the Departments of <sup>1</sup>Neurology and <sup>3</sup>Ophthalmology, Zürich University Hospital, Switzerland; and <sup>2</sup>Department of Neurology, Johns Hopkins Hospital, Baltimore, Maryland.

Supported by the Swiss National Science Foundation (3231-051938.97/3200-052187.97); the Betty and David Koetser Foundation for Brain Research, Zürich, Switzerland; and National Institutes of Health Grant RO1-EY01849.

Submitted for publication June 28, 2000; revised November 3, 2000; accepted November 22, 2000.

Commercial relationships policy: N.

Corresponding author: Dominik Straumann, Neurology Department, Zürich University Hospital, Frauenklinikstrasse 26, CH-8091 Zürich, Switzerland. dominik@neurolog.unizh.ch

in four patients with trochlear nerve palsy before and after eye muscle surgery.

## METHODS

### Setup

Ocular rotation of both eyes about all three principal axes (torsional, roll,  $x$ -axis; horizontal, pitch,  $y$ -axis; vertical, yaw,  $z$ -axis) was simultaneously recorded with dual search coils manufactured by Skalar (Delft, The Netherlands). Dual search coils combine two coils: one is oriented in the frontal plane; the other, wound in a figure-eight-fashion, has its effective area approximately along the line-of-sight. Both coils are embedded in a self-adhering silicone annulus placed around the cornea. A dual search coil costs ~300 US\$ and can be reused with proper disinfection up to 10 times.

The field system consisted of a cubic coil frame of welded aluminum that produces three orthogonal magnetic fields with frequencies of 55.5, 83.3, and 41.6 kHz and intensities of 0.088 Gauss. Amplitude-modulated signals were extracted by synchronous detection (modified Rimmel system).<sup>17</sup> The bandwidth of the system was 0 to 90 Hz. Peak-to-peak noise signals in all three principal directions after calibration, as measured by a dual search coil placed in the center of the magnetic frame, were about 0.1°.

### Calibration Procedure

The major part of the calibration was done *in vitro*, that is, with no subject participation required. This property of the procedure is especially useful for eye movement recordings of patients in whom *in vivo* calibrations by a fixation task are difficult or impossible. The voltage offsets of the system were zeroed with the dual search coils in the center of a soft iron tube that shielded the coils from the magnetic fields.<sup>18</sup> Thereafter, the relative gains of the three-magnetic fields were determined with the search coils on a gimbal system placed in the center of the coil frame. The details of the calibration procedure are given in Appendix I.

The three-dimensional eye position in the magnetic coil frame was expressed in rotation vectors. A rotation vector  $\mathbf{r} = (r_x, r_y, r_z)$  describes the instantaneous orientation of a body as a single rotation from the reference position; the vector is oriented parallel to the axis of this rotation, and its length is defined by  $\tan(\rho/2)$ , where  $\rho$  is the rotation angle. The three head-fixed orthogonal axes of the coil frame define the coordinate system of rotation vectors, with the  $x$ -axis pointing forward, the  $y$ -axis leftward, and the  $z$ -axis upward. The signs of rotations about these cardinal axes are determined by the right-hand rule, that is, clockwise, leftward, and downward rotations, as seen from the subject's view, were positive. The algorithm for converting the raw data into rotation vectors is described in Appendix II. The transformation of rotation vectors, which express ocular positions in a head coordinate frame, to gaze angles for the interpretation by the clinician is elaborated on in Results.

### Hess Screen Test

Subjects were seated inside the magnetic field coil (side length, 1.4 m) so that the center of the interpupillary line coincided with the center of the frame. The head of the subject was immobilized with a bite bar that was oriented along earth-horizontal. Dual search coils were mounted on both eyes, after anesthetizing the conjunctiva and cornea with proparacaine HCl 0.5% (Ophthalmic; Allergan, Irvine, CA).

During measurements, subjects monocularly fixed on dots on a tangent screen at a distance of 1.24 m at its center, while the other eye was covered. The dots were located straight-ahead and at eight eccentric positions (horizontal and vertical coordinates in degrees: [0, 20]; [20, 20]; [20, 0]; [20, -20]; [0, -20]; [-20, -20]; [-20, 0]; [-20, 20]). The dots were arranged as a square with straight sides 20° from the center fixation point, that is, a "Harms" type projection. The entire procedure lasted about 20 minutes. Voltages related to the orientation

of the eye coils in the magnetic coil frame were digitized with a 16-bit A/D converter at 1000 Hz and written to a hard disc. The data were analyzed off-line in MATLAB Version 5.4.

### Torsional Coil Slippage

During search coil recordings, one frequently observes a long-term drift of torsional coil signals, which is due to a gradual slippage of the silicon annulus on the conjunctiva about the line-of-sight.<sup>19,20</sup> To minimize this problem off-line, the torsional position was reset to the value measured at the beginning of a trial during each straight-ahead fixation. Thus, the values of torsion at eccentric positions were always relative to the value of torsion at the reference (0,0) fixation position. The absolute value of torsion cannot be measured with the search coil technique.

### Subjects

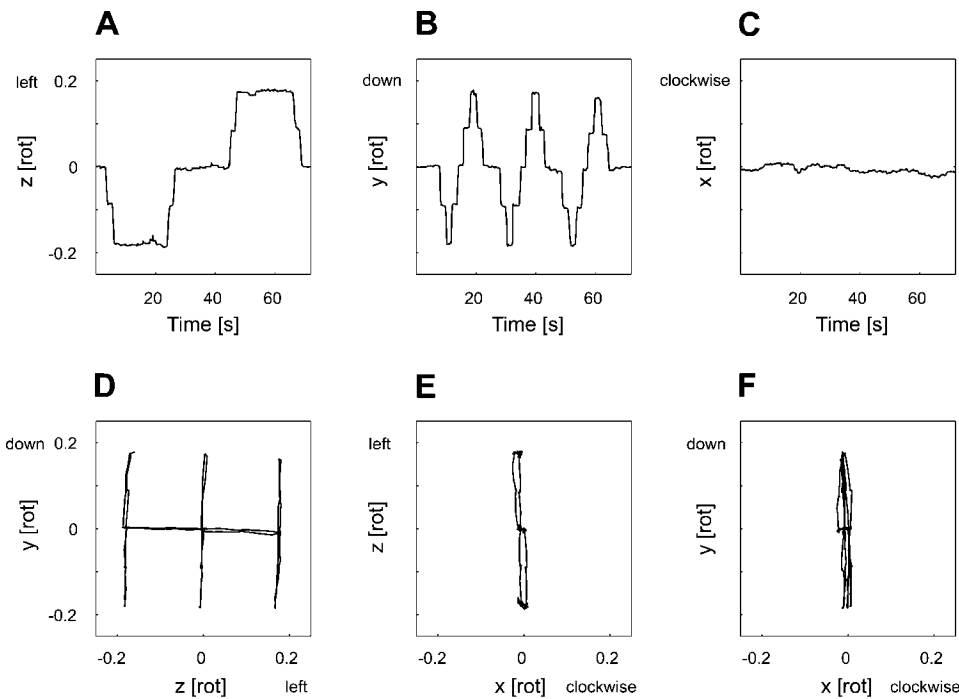
In the Results section of this article, typical data of an orthotropic subject, three patients with acquired trochlear nerve palsy and two patients with congenital trochlear nerve palsy are presented. Experimental protocols adhered to the Declaration of Helsinki for research involving human subjects (adopted by the 18th World Medical Assembly, Helsinki, Finland, 1964, and as revised last in Hong Kong in 1989) and approved by the local Ethical committee.

## RESULTS

Figure 1 shows an example of rotation vectors from the right eye of an orthotropic subject who fixed on the different target points on the tangent screen. On the first row, horizontal ( $z$ ; Fig. 1A), vertical ( $y$ ; Fig. 1B), and torsional ( $x$ ; Fig. 1C) rotation vector components are plotted as a function of time. The torsional movements were minimal. On the second row of Figure 1, the three components of the same rotation vectors are plotted against each other in the front ( $z$ - $y$  projection; Fig. 1D), side ( $x$ - $z$  projection; Fig. 1E), and top ( $x$ - $y$  projection; Fig. 1F) views. The data points formed a plane because the fixations and movements of the measured eye obeyed Listing's law. Here, the plane was almost parallel to the  $y$ - $z$  plane of the coordinate system; therefore, the data cloud appeared thin in both the side and top views. It should be stressed that the front view does not exactly represent the horizontal-vertical direction of the line-of-sight but represents the horizontal and vertical components of rotation vectors.

The rotation vectors follow the right-hand rule (see Methods), that is, leftward and downward movements are positive. Hence, compared with a standard two-dimensional Hess screen graph, Figure 1D is inverted both in the horizontal and vertical directions.

The nine data clouds of rotation vectors associated with target fixations were selected with an interactive computer program. Then, the median of the three-dimensional rotation vector was computed for each target point. Figure 2 depicts examples of binocular recordings from an orthotropic subject and a strabismic patient. For better visualization, the eccentric values are connected with the central value. The left column (Figs. 2Aa, Ab, Ac) is based on the same right eye data as the previous figure, with the covered right eye in blue and the viewing left eye in red. The right column (Figs. 2Ba, Bb, Bc) shows the data of a patient with an acquired trochlear nerve palsy of the right eye. Again, the covered right eye (paretic) is in blue and the viewing left eye (healthy) is in red. The panels of each row illustrate the front (Figs. 2Aa, Ba), side (Figs. 2Ab, Bb), and top (Figs. 2Ac, Bc) views of median three-dimensional eye rotation vectors. To make the front view (horizontal-vertical projection) comparable with a standard two-dimensional Hess test, both the  $y$ - and  $z$ -components were multiplied by  $(-1)$ . Hence, in the two panels on the top row, rightward



**FIGURE 1.** Example of rotation vectors of the right eye in an orthotropic subject during fixation of the targets on the Hess screen. Horizontal (A), vertical (B), and torsional (C) rotation vector components as a function of time. Rotation vectors are also shown in the front (D), side (E), and top (F) view.

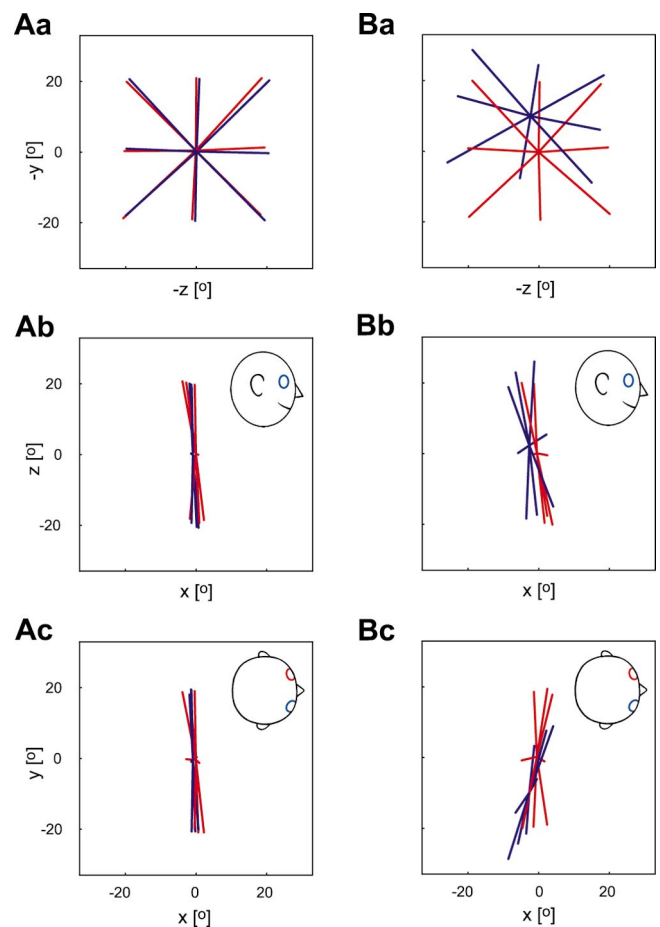
and upward movements are positive. The three-dimensional orientation of the axes about which the eyes rotated with respect to the head (see inserted heads) can easily be identified in the views from the right side (Figs. 2Ab, Bb) and from the top (Figs. 2Ac, Bc).

There were only minimal horizontal, vertical, and torsional deviations between both eyes in the orthotropic subject, as visualized in all three projections (Figs. 2Aa, Ab, Ac). Again, the data points were closely restricted to a plane, in accordance with Listing's law. In the front view (Fig. 2Ba), the patient showed a right over left eye position, with an increase of vertical deviation with leftward gaze. In the side view (Fig. 2Bb), the plane of the right eye appeared "thicker" than the plane of the left eye. The reason for this difference in the thickness of the plane becomes evident in the top view (Fig. 2Bc): The plane of the right eye is rotated temporally; therefore, the side view is not parallel to this plane, but oblique. In fact, the real plane thickness of the right eye, which is expressed as the SD of the nine data points from the best-fit plane, was less ( $0.59^\circ$ ) than the plane thickness of the left eye ( $0.71^\circ$ ). These values were within the SDs measured for orthotropic subjects.<sup>20</sup>







The following procedures (formulae given in Appendix III) were applied to the nine median rotation vectors<sup>21</sup>: (1) the vertical-horizontal gaze direction in degrees was computed. (2) The gaze direction was inverted both in the horizontal and vertical directions, such that upward and rightward became positive. This convention is equivalent to the one used for the standard two-dimensional Hess screen test, in which the coordinates are plotted from the subject's perspective, that is, from behind ("right is right, up is up"). (3) The torsional component of the rotation vectors was converted to degrees.

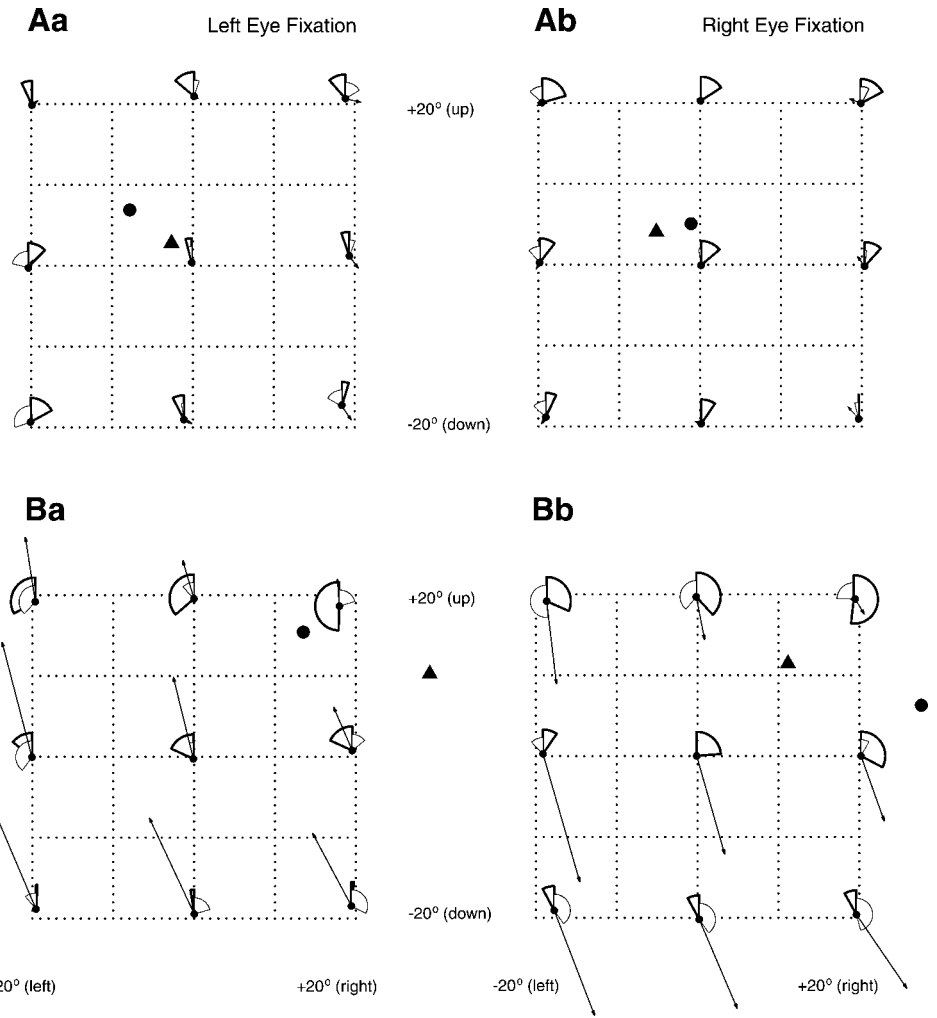
Figure 3 contains the same data as in the previous figure, but here we attempted to help the clinician to grasp immediately the three-dimensional eye position of the viewing eye and, at the same time, the three-dimensional alignment between the viewing and the covered eye, in a single panel.

The small dots indicate the median horizontal and vertical directions of the line-of-sight of the fixing eye in the orthotropic subject (Figs. 3Aa, Ab) and the patient (Figs. 3Ba, Bb). In



**FIGURE 2.** Examples of median three-dimensional eye rotation vectors of an orthotropic subject (A, left column) and a patient with a right-sided acquired trochlear nerve palsy (B, right column). Rotation vectors in the front (Aa, Ba), side (Ab, Bb), and top (Ac, Bc) view. Blue, right eye; red, left eye.

- LEGEND
-  cyclovergence [ °/hour ]
  -  horizontal and vertical vergence
  -  torsional position of viewing eye [ °/hour ]
  -  horizontal and vertical position of viewing eye
  -  primary position of viewing eye
  -  primary position of covered eye



**FIGURE 3.** Three-dimensional eye positions of the viewing eye, three-dimensional vergence, and primary positions of both eyes in the orthotropic subject (A) and the patient (B) with a right-sided acquired trochlear nerve palsy; (a) left eye viewing; (b) right eye viewing. Directions from the subject's viewpoint: *Small dots*: median horizontal and vertical directions of the line-of-sight of the fixating eye; *arrows*: two-dimensional vectors of horizontal and vertical vergence between the two eyes; *thicker-stroked sectors*: amounts of cyclovergence; *thinner-stroked sectors with small radius*: torsional rotation vector components of the fixating eye. Unit of sectors: 1 hour corresponds to 1° of torsion, with zero torsion at 12 o'clock; also, the direction of torsion is defined from the perspective of the subject.

the left column, the left eye is viewing (Figs. 3Aa, Ba); in the right column, the right eye is viewing (Figs. 3Ab, Bb). The arrows represent the two-dimensional vectors of the horizontal and vertical vergence between the two eyes; hence, the endpoint of each arrow corresponds to the horizontal and vertical direction of the line-of-sight of the covered eye.

Two sectors are depicted at each fixation dot of the viewing eye. The sectors with the smaller radius (thinner stroke) describe the torsional rotation vector components of the fixing eye. The following scale was adopted: 1 hour corresponds to 1° of torsion, with zero torsion at 12 o'clock; the direction of torsion is defined from the perspective of the subject. For example, 3 hours of counterclockwise rotation of left fixing eye corresponds to an excyclorotation by 3°. If the right eye is fixing, the same sector corresponds to an incyclorotation by 3°. The sectors with the larger radius (thicker stroke) give the amount of cyclovergence. The same scale was adopted as for the torsional component of the fixing eye. For example, with the left eye viewing, 2 hours of counterclockwise rotation means a relative 2° incyclorotation of the covered right eye with respect to the viewing left eye, that is, a 2° incyclovergence. If the right eye is viewing, 2 hours of clockwise rotation means a relative 2° incyclorotation of the covered left eye with respect to the viewing right eye, and again, a 2° incyclovergence.

The large filled circle and the large filled triangle show the primary positions of the fixating eye and the covered eye, respectively. Primary position was determined by fitting a

plane through the data cloud of the nine median rotation vectors:

$$x = a_0 + a_1 \cdot y + a_2 \cdot z$$

where

The horizontal ( $p_h$ ) and vertical ( $p_v$ ) components of primary position in degrees are directly computed from the slopes of the regression<sup>21</sup>:

$a_0$  = the offset along the  $x$ -axis,

$a_1$  = the  $y$ -slope,

$a_2$  = the  $z$ -slope.

$$p_h = 2 \cdot a_1 \cdot \frac{180}{\pi}, \quad p_v = -2 \cdot a_2 \cdot \frac{180}{\pi}$$

whereby rightward and upward components are positive, as in the standard two-dimensional Hess screen test. We will elaborate on the clinical significance of primary position in the Discussion.

In the orthotropic subject, there was a small exophoria of less than 2°, independent of whether the left (Fig. 3Aa) or the right (Fig. 3Ab) eye was viewing. There was a slight right

hyperphoria in left gaze and a left hyperphoria during fixations along the vertical meridian and in left gaze. The vertical phoria was always less than 2°. The torsional phoria never exceeded 3°. This value for torsional phoria is a relative quantity because the torsion measured in each eye at a given position was always referenced to the torsion in the straight-ahead viewing position (= reference position). The horizontal-vertical directions of the line-of-sight of both eyes were all close to the fixation targets. Independent of which eye was fixing, the primary viewing positions of both the viewing (filled circle) and the covered (filled triangle) eyes were located above the horizontal meridian and slightly shifted to the left.

In the patient (Figs. 3Ba, Bb), the eye with the acquired trochlear nerve palsy (right eye) was deviated upwards; the right eye over left eye position was maximal in adduction and downward gaze. Compared with the measurement with the left eye viewing (Fig. 3Ba), the vertical deviation was larger during fixation with the palsied right eye (Fig. 3Bb), that is, the secondary deviation exceeded the primary deviation. There was a striking gradient of increasing horizontal and vertical misalignment from right-upward to left-downward gaze. The gradient of excyclovergence pointed in the same direction. The left eye showed a gradient of increasing excyclorotation from right-down to left-up gaze. This gradient was parallel to the gradient of increasing incyclorotation of the right eye. The primary position of the paretic right eye was shifted to the right, that is, temporally, by almost 30°; the primary position of the left eye was displaced in the same direction, that is, nasally, by about half the amount. The locations of the primary positions were similar during fixation with the left (L; healthy) or right (R; paretic) eye, thus relatively independent of which eye was fixing.

Figure 4 provides a summary of the alignment values in the orthotropic subject (Fig. 4A), and in the patient with the right-sided acquired trochlear nerve palsy (Fig. 4B), from the subject's viewpoint. The numbers are based on the same fixation trial as shown in the previous figure with the left eye viewing. For each direction of gaze, horizontal (Exo or Eso), vertical (right eye position higher than left eye position [R/L] or L/R), and torsional (Excyc or Incyc) vergence are quantified. The horizontal and vertical numbers specify the direction of gaze, whereas the torsional numbers correspond to the torsional component of the rotation vector. The inset above the main table gives the horizontal (adduction [Add] or abduction [Abd]) and vertical (elevation [Ele] or depression [Dep]) direction of the primary position (PP) for both eyes.

## DISCUSSION

Here we provide methodological and analytical procedures to perform a three-dimensional Hess screen test with binocular dual search coils. The three-dimensional ocular positions were used to describe the horizontal, vertical, and torsional vergence angles as well as the primary positions of both eyes. These parameters were presented using a concise graphical description. This test has several advantages: (1) it is objective; (2) it allows one to compare the primary positions of both eyes; and, (3) it gives information on torsional alignment. In particular, we will elaborate on the importance of the torsional degree of freedom of both eyes with respect to the primary position and to torsional alignment.

The term "primary position" was originally introduced by Helmholtz<sup>5</sup>: "Among the different eye positions, one can be found from which a movement, up or down, right or left, does not introduce rotation about the line-of-sight. This position is called primary gaze direction." Clearly, in Helmholtz' definition, primary (gaze) position does not necessarily coincide

## A

Left Eye Fixation

PP right Eye	Add 2.6°	Ele 2.8°
PP left Eye	Abd 7.8°	Ele 6.9°

Exo 0.8° R/L 0.6° Incyc 0.8°	Exo 0.6° L/R 0.3° Incyc 1.7°	Exo 1.9° L/R 0.5° Incyc 1.4°
Exo 0.6° R/L 1.0° Excyc 1.5°	Exo 0.3° L/R 0.3° Incyc 0.5°	Exo 1.1° L/R 1.5° Incyc 0.6°
Exo 0.3° R/L 1.0° Excyc 2.0°	Exo 1.0° L/R 0.5° Incyc 0.9°	Exo 1.2° L/R 1.7° Excyc 0.5°

## B

Left Eye Fixation

PP right Eye	Abd 29.1°	Ele 10.3°
PP left Eye	Add 13.5°	Ele 15.4°

Eso 1.2° R/L 8.0° Incyc 4.0°	Eso 1.4° R/L 4.8° Incyc 4.4°	Eso 0.3° R/L 3.4° Incyc 5.9°
Eso 3.7° R/L 14.3° Incyc 1.7°	Eso 2.5° R/L 10.1° Incyc 2.2°	Eso 2.3° R/L 5.4° Incyc 2.2°
Eso 6.5° R/L 15.3° Excyc 0.1°	Eso 5.6° R/L 11.9° Incyc 0.3°	Eso 4.8° R/L 9.0° Excyc 0.2°

FIGURE 4. Numerical scheme of vergence and primary positions (PP) in the orthotropic subject (A) and the patient with a right-sided acquired trochlear nerve palsy (B). Horizontal (Exo or Eso), vertical (R/L or L/R), and torsional (Excyc or Incyc) vergence are from the patient's viewpoint. *Inset*: horizontal (Add or Abd) and vertical (Ele or Dep) components of primary positions of both eyes. Directions are from the subject's viewpoint.

with gaze straight ahead. If, for instance, an eye intorts when looking up and extorts when looking down from the straight-ahead position, primary position lies to the temporal side from the straight-ahead position.

Primary position is directly related to Listing's law: If primary position is chosen as the reference position, all other eye positions can be reached from this position by a rotation about an axis that is perpendicular to the direction of gaze in primary position.<sup>5</sup> In this case, rotation vectors lie in the frontal plane of the coordinate system. If primary position deviates from the reference position, the plane of these rotation axes—so called Listing's plane—is rotated in the direction of primary position by half the angle.<sup>21,22</sup> In orthotropic subjects, in the presence of convergence, the primary positions of both eyes move temporally,<sup>23,24</sup> but not by the whole amount that is required to strictly preserve the sensory requirement of retinal correspondence.<sup>25</sup> Only if the primary positions of both eyes coincide is there no torsional disparity for targets at infinite distance. Normally, however, the primary positions of the two eyes are not exactly aligned, which leads to different torsional disparities at different gaze directions. Because torsional disparity can be fused centrally to a certain degree,<sup>26</sup> the amount of torsional vergence in different gaze directions cannot be directly related to the magnitude of torsional diplopia.

Perhaps the main significance of primary position for the clinician is its relationship to the pulling directions of the different extraocular muscles. To a first approximation, the axes about which the eye rotates are determined by the vectorial summation of the forces of the six extraocular muscles. The contraction of each muscle in isolation leads to a rotation of the eye about an axis that is perpendicular to the pulling

direction of this muscle. For instance, the activation of the superior oblique muscle rotates the ocular globe from the straight-ahead position about an axis that nearly lies in the horizontal plane ( $x$ - $y$  plane) and forms an angle of approximately  $35^\circ$  with the sagittal axis ( $x$ -axis).<sup>27</sup> If eye movements were accomplished by contraction and relaxation of this muscle only, the horizontal component of primary position would be located in the nasal direction (recall the definition of primary position). In the case of an eye muscle palsy, we propose that the primary position produced by the remaining five muscles can be predicted by vectorially subtracting the primary position of the palsied muscle from the primary position measured with all eye muscles intact. On the basis of this hypothesis, we speculate that the change of primary position is largest in palsies that affect eye muscles with major torsional components of their pulling direction, that is, especially the oblique and vertical recti muscles. On the other hand, we expect that palsies of the horizontal recti would not lead to major changes of primary position, unless there is compensation by other muscles with torsional pulling directions. In our example of isolated acquired right trochlear nerve palsy, the *primary position of the paretic eye* moved temporally, as one would predict (Fig. 3B). Changes of the location of extraocular muscle pulleys could also play a role in modifying primary position<sup>28</sup>: In patients with a superior oblique muscle palsy, the pulley of the medial rectus muscle showed an upward displacement, probably as a consequence of the atrophy of the adjacent superior oblique muscle belly.<sup>29</sup>

Interestingly, in our example of a right-sided trochlear nerve palsy (Fig. 3B), the primary position of the *healthy eye* is located in the nasal hemifield by more than  $10^\circ$ , thus minimizing the "horizontal deviation" of both primary positions. This phenomenon could be explained by a compensatory decreased activity of the inferior rectus muscle of the healthy left eye (yoke muscle), which would lead to an increased intorsion as the eye moves down. Also, changes in the neural control of extraocular muscle pulleys could lead to modifications of Listing's plane and, hence, of primary position of the healthy eye.<sup>30</sup> The horizontal and vertical difference between the primary positions of the two eyes is directly related to the gradients of cyclovergence as a function of gaze direction. In the example of the patient with a right acquired trochlear nerve palsy (Fig. 3B), there is a gradient of increasing incyclovergence from downward to upward gaze. This gradient means that the rotation axes for vertical movements of the two eyes are not parallel but form an angle that points forward.

Figure 5 schematically explains the relation between the vertical gradient of torsional vergence and the horizontal component of primary position. In Figure 5A, both eyes are depicted from above (top view). The horizontal axis about which the left eye rotates to move upward is in the frontal plane; thus, primary position coincides with the straight-ahead position. On the other hand, the horizontal axis of the right eye with the acquired trochlear nerve palsy is tilted outward by  $\alpha/2 = 15^\circ$ , and the primary position of this eye is rotated  $\alpha = 30^\circ$  to the right. For mathematical reasons, the shift of primary position is always twice the angle of the rotation axis.<sup>21</sup> Because of the outward tilt of the rotation axis, an upward movement of the right eye is associated with an intorsional movement of the ocular globe with respect to the head (In this context, "torsion" is defined as a rotation about the  $x$ -axis in the head-fixed coordinate system and not a rotation about the line-of-sight). This leads to a gradient of increasing incyclovergence when the patient is changing his eye position from downward to upward.

Figure 5B shows the retinas of both eyes seen from behind. The crosses indicate the torsional orientation of the retina during straight-ahead gaze (dashed) and  $\epsilon = 20^\circ$  upward gaze

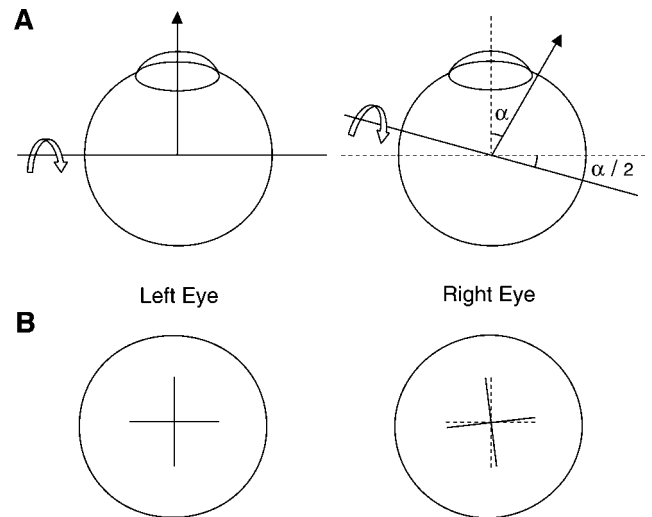


FIGURE 5. Schematic top (A) and back (B) views of both eyes in a patient with a right-sided acquired trochlear nerve palsy. The eyes rotate about the depicted axes to move upward from the straight-ahead position. (A) Left eye: axis is in the frontal plane; right eye: axis is rotated in the temporal direction by  $\alpha/2 = 15^\circ$ . Therefore, the primary position of the right eye points temporally by  $\alpha = 30^\circ$ . (B) Orientation of the retina during gaze straight ahead (*dashed cross*) and during  $20^\circ$  elevation (*solid cross*). Only the retina of the right eye intorts ( $\tau = 5.1^\circ$ ) about the line-of-sight.

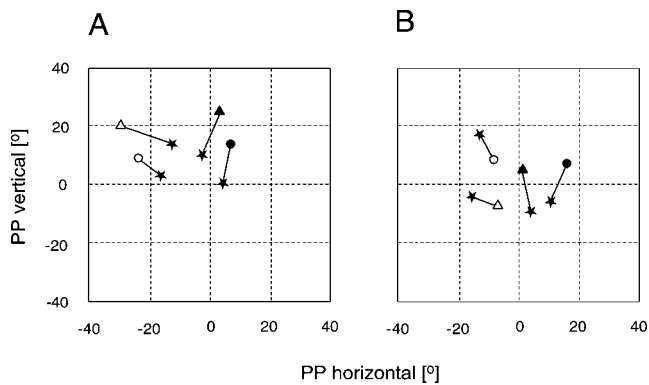
(solid). Clearly, in the left eye, both crosses coincide, whereas in the right eye, there is an intorsion of the retina in upgaze by  $\tau = 5.1^\circ$ . In fact, the retinal torsion during vertical eye movements ( $\tau$ ) is a function of the horizontal component of primary position ( $\alpha$ ) and the elevation of gaze ( $\epsilon$ ):

$$\tau = \frac{\alpha}{2} \cdot \sin(\epsilon)$$

The definition of primary position formulated by Helmholtz<sup>5</sup> does not necessitate that eye positions follow Listing's law. The only requirement is that a linear relation between gaze direction and torsion exists along secondary positions (horizontal and vertical meridians). In the example of an eye with acquired trochlear nerve palsy, however, Listing's law is preserved (Fig. 2B). Thus, in this case, primary position computed from the orientation of Listing's plane is equivalent to the definition of Helmholtz.

To date, little is known about the location of primary position in the presence of a concomitant strabismus. Melis et al.<sup>31</sup> reported on a subject with a concomitant alternating strabismus, in which the Listing's planes of the two eyes varied depending on whether the right or the left eye was viewing.

To what extent Listing's law is still obeyed in the presence of extraocular muscle palsy before and after surgery is presently being investigated with the three-dimensional Hess screen test. So far, no statistical data are available, but there are clear indications that muscle surgery on *one* eye changes the primary position of *both* eyes: Figure 6 demonstrates how both eyes' primary positions are affected by a contralateral inferior rectus recession in typical patients with a left-sided trochlear nerve palsy. In all four patients the primary position of the healthy eye moved downward as a result of the operation. There was, however, a differential effect of the surgery on the primary position of the paretic eye, depending on whether the palsy was acquired or congenital. In the patients with the acquired palsy (Fig. 6A), the temporally displaced primary position moved closer to the vertical meridian, but in the



**FIGURE 6.** Effect of contralateral inferior rectus recession on the primary positions (PP) of both eyes in four patients with left-sided trochlear nerve palsy. **▲, ●:** primary position of the right eye before surgery; **△, ○:** primary position of the left eye before surgery. **★:** primary position after surgery. **(A)** Two patients (circles, triangles) with acquired trochlear nerve palsy; **(B)** two patients (circles, triangles) with congenital trochlear nerve palsy.

patients with the congenital palsy (Fig. 6B), the primary position moved in the temporal direction. Whether this finding can be generalized remains to be explored, but this example demonstrates that eye muscle surgery has a direct effect on the primary position, and, hence, the three-dimensional orientation of ocular rotation axes.

In conclusion, the three-dimensional Hess screen test with dual search coils allows one to describe the deviations of both eyes around all principal axes of eye rotation (horizontal, torsional, vertical) during monocular fixation of eccentric targets. In contrast to standard methods that also measure cyclo-deviation, such as the Maddox double-rod, the Harms tangent scale, and the Lancaster red-green tests, the Hess screen test with dual search coils is objective. Although the search coil technique is semi-invasive, rather costly, and only applicable in cooperating subjects (age > 10 years), the high precision of the data provided by the dual-search coil Hess screen test has considerable potential in the evaluation of and planning of therapy for patients with strabismus.

### Acknowledgment

The authors thank Heimo Steffen for sharing his clinical experience.

### References

- Hess WR. Ein einfaches messendes Verfahren zur Motilitätsprüfung der Augen. *Zeitschrift für Augenheilkunde*. 1916;15:201-219.
- Zee DS, Chu FC, Optican LM, et al. Graphic analysis of paralytic strabismus with the Lancaster red-green test. *Am J Ophthalmol*. 1984;97:587-592.
- Donders FC. Beiträge zur Lehre von den Bewegungen des menschlichen Auges. *Holländische Beiträge zu den Anatomischen und Physiologischen Wissenschaften*. 1848;1:105-145.
- Ruete CGT. *Lehrbuch der Ophthalmologie*. Braunschweig: Vieweg; 1855.
- Helmholtz HV. *Handbuch der Physiologischen Optik*. Hamburg und Leipzig: L. Voss; 1867.
- Graefe von A. Über die ophthalmoskopische Beobachtung gewisser Augenmuskelwirkungen. *Graefes Arch Ophthalmol*. 1855;2:322.
- Bixenman WW, von Noorden GK. Apparent foveal displacement in normal subjects and in cyclotropia. *Ophthalmology*. 1982;89:58-62.
- Bagolini B. Ricerche sul comportamento della "convergenza prosimale" in soggetti strabici e normali (rilievi mediante determinazione al sinottoforo e con prismi). *Boll Ocul*. 1961;40:461.

- Somani RAB, Hutnik C, DeSouza JFX, et al. Using a synoptophore to test Listing's law during vergence in normal subjects and strabismic patients. *Vision Res*. 1998;38:3621-3631.
- Harms H. Über die Untersuchung der Augenmuskellähmungen. *Graefes Arch Ophthalmol*. 1941;144:129.
- Lancaster WB. Detecting, measuring, plotting and interpreting ocular deviations. *Arch Ophthalmol*. 1939;22:867-880.
- Hering E. *Die Lehre vom binokularen Sehen*. Leipzig: Englemaun, 1868.
- Robinson DA. A method of measuring eye movement using a scleral search coil in a magnetic field. *IEEE Trans Biomed Eng*. 1963;10:137-145.
- Collewijn H, Van der Mark F, Jansen TC. Precise recording of human eye movements. *Vision Res*. 1975;15:447-450.
- Collewijn H, Van der SJ, Ferman L, et al. Human ocular counterroll: assessment of static and dynamic properties from electromagnetic scleral coil recordings. *Exp Brain Res*. 1985;59:185-196.
- Ferman L, Collewijn H, Jansen TC, et al. Human gaze stability in the horizontal, vertical and torsional direction during voluntary head movements, evaluated with a three-dimensional scleral induction coil technique. *Vision Res*. 1987;27:811-828.
- Rommel RS. An inexpensive eye movement monitor using the scleral search coil technique. *IEEE Trans Biomed Eng*. 1984;31:388-390.
- Straumann D, Zee DS, Solomon D, et al. Transient torsion during and after saccades. *Vision Res*. 1995;35:3321-3334.
- Van Rijn LJ, Van der Steen J, Collewijn H. Instability of ocular torsion during fixation: cyclovergence is more stable than cycloversion. *Vision Res*. 1994;34:1077-1087.
- Straumann D, Zee DS, Solomon D, et al. Validity of Listing's law during fixations, saccades, smooth pursuit eye. *Exp Brain Res*. 1996;112:135-146.
- Hausteil W. Considerations on Listing's law and the primary position by means of a matrix description of eye position control. *Biol Cybernet*. 1989;60:411-420.
- Tweed D, Vilis T. Implications of rotational kinematics for the oculomotor system in three dimensions. *J Neurophysiol*. 1987;58:832-849.
- Mok D, Ro A, Cadera W, et al. Rotation of Listing's plane during vergence. *Vision Res*. 1992;32:2055-2064.
- Steffen H, Walker MF, Zee DS. Rotation of Listing's plane with convergence: independence from eye position. *Invest Ophthalmol Vis Sci*. 2000;41:715-721.
- Tweed D. Visual-motor optimization in binocular control. *Vision Res*. 1997;37:1939-1951.
- Kertesz AE, Sullivan MJ. The effect of stimulus size on human cyclofusional response. *Vision Res*. 1978;18:567-571.
- Volkman AW. Zur Mechanik der Augenmuskeln. *Ber d Königl Sächs Ges d Wissensch Leipzig Math Phys Classe I*. 1869;28.
- Demer JL, Miller JM, Poukens V, et al. Evidence for fibromuscular pulleys of the recti extraocular muscles. *Invest Ophthalmol Vis Sci*. 1995;36:1125-1136.
- Clark RA, Miller JM, Demer JL. Displacement of the medial rectus pulley in superior oblique palsy. *Invest Ophthalmol Vis Sci*. 1998;39:207-212.
- Demer JL, Oh SY, Poukens V. Evidence for active control of rectus extraocular muscle pulleys. *Invest Ophthalmol Vis Sci*. 2000;41:1280-1290.
- Melis BJM, Cruysberg JRM, Van Gisbergen JAM. Listing's plane dependence on alternating fixation in a strabismus patient. *Vision Res*. 1997;37:1355-1366.

### APPENDIX I

The purpose of the in vitro calibration is to determine the gains of the signals in each coil induced by the three orthogonal magnetic fields. This procedure, which is performed before each experiment, requires that the magnetic fields are orthogonal.

Constant offset voltages (undesirable pickup, internal amplifier biases) are compensated by placing the annulus in a soft

iron tube, which isolates the search coils from the magnetic fields, and setting the offset knobs of the amplifier to zero. Then, after the annulus is removed from its shield, all signals at the output of the detector are due to the search coils alone.

After the offsets are nulled, the annulus is placed on a gimbal system and rotated in six positions, each of which picks up the maximum voltage induced by one magnetic field in one search coil (two coils times three directions for each eye). The alignment of the two search coil sensitivity vectors with the magnetic field must follow the right-hand rule to obtain the maximal amplitudes with the correct signs, that is, the coil sensitivity vectors must be aligned in sequence with the  $x$ -axis (pointing forward), the  $y$ -axis (pointing leftward), and the  $z$ -axis (pointing upward).

Once the offsets are eliminated and the measurement of the magnetic fields completed, the raw signals can be used to compute the orientation of the dual search coil in the space-fixed magnetic frame. For each moment in time, the computer calculates the rotation necessary to move the dual search coil from a defined reference position to the instantaneous position (algorithm see Appendix II). The reference position is usually defined as the position when the line-of-sight is directed to a specified straight-ahead target that is far enough away so the vergence angle is negligible.

### APPENDIX II

First, the relative maximal amplitudes ( $g_{D_x}, g_{D_y}, g_{D_z}, g_{T_x}, g_{T_y}, g_{T_z}$ ) induced by the three magnetic fields ( $x, y, z$ ) and measured from the two search coils (D, direction coil; T, torsion coil) are computed by dividing the maximal voltages ( $v_{D_x}, v_{D_y}, v_{D_z}, v_{T_x}, v_{T_y}, v_{T_z}$ ) by the values induced by the  $z$ -field ( $v_{D_z}, v_{T_z}$ ):

$$\mathbf{g}_D = \begin{pmatrix} g_{D_x} \\ g_{D_y} \\ g_{D_z} \end{pmatrix} = \begin{pmatrix} v_{D_x} \\ v_{D_y} \\ v_{D_z} \end{pmatrix} \div |v_{D_z}| \quad \mathbf{g}_T = \begin{pmatrix} g_{T_x} \\ g_{T_y} \\ g_{T_z} \end{pmatrix} = \begin{pmatrix} v_{T_x} \\ v_{T_y} \\ v_{T_z} \end{pmatrix} \div |v_{T_z}|$$

Each sample of the signal from the two coils during the eye movement recording consisted of six voltages: three values from the direction coil ( $s_{D_x}, s_{D_y}, s_{D_z}$ ) and three values from the torsion coil ( $s_{T_x}, s_{T_y}, s_{T_z}$ ). These voltages are divided by the field gains ( $\mathbf{g}_D$ ) and ( $\mathbf{g}_T$ ):

$$\mathbf{d} = \begin{pmatrix} d_x \\ d_y \\ d_z \end{pmatrix} = \begin{pmatrix} s_{D_x} \\ s_{D_y} \\ s_{D_z} \end{pmatrix} \div \begin{pmatrix} g_{D_x} \\ g_{D_y} \\ g_{D_z} \end{pmatrix} \quad \mathbf{t} = \begin{pmatrix} t_x \\ t_y \\ t_z \end{pmatrix} = \begin{pmatrix} s_{T_x} \\ s_{T_y} \\ s_{T_z} \end{pmatrix} \div \begin{pmatrix} g_{T_x} \\ g_{T_y} \\ g_{T_z} \end{pmatrix}$$

Because the maximal amplitudes of the induced voltages during calibration are measured according to the right-hand rule (see Appendix I), this rule is automatically preserved by this division, independent of the signs of the raw signals.

Each sample now consists of two vectors that are non-orthogonal, because the effective surfaces of the search coils in the annulus usually do not form a perfect 90° angle. Thus, the next step is to orthogonalize the sensitivity vector of the torsion coil ( $\mathbf{t}$ ) to the sensitivity vector of the direction coil ( $\mathbf{d}$ ). First, we normalize the vector of the direction coil:

$$\mathbf{f}^1 = \mathbf{d} \div \|\mathbf{d}\|$$

Then  $\mathbf{t}$  is projected onto  $\mathbf{f}^1$  by the scalar product:

$$\mathbf{t}' = (\mathbf{t} \cdot \mathbf{f}^1) \mathbf{f}^1$$

The orthogonalized vector of the torsion coil ( $\mathbf{t}''$ ) is calculated by the vectorial subtraction:

$$\mathbf{t}'' = \mathbf{t} - \mathbf{t}'$$

Thereafter,  $\mathbf{t}''$  is normalized:

$$\mathbf{f}^2 = \mathbf{t}'' \div \|\mathbf{t}''\|$$

A third sensitivity vector ( $\mathbf{f}^3$ ) orthogonal to the other two orthogonal sensitivity vectors is computed by the cross product:

$$\mathbf{f}^3 = \mathbf{f}^1 \times \mathbf{f}^2$$

The three orthogonal normalized vectors form the eye-fixed base vectors ( $\mathbf{f}^1, \mathbf{f}^2, \mathbf{f}^3$ ). Hence, the three-dimensional eye position at each moment in time is represented by the matrix  $f$  that consists of the three normalized orthogonal vectors:

$$f = [\mathbf{f}^1 \ \mathbf{f}^2 \ \mathbf{f}^3]$$

Next, the rotation matrix ( $R$ ) describing the rotation of the three orthogonal vectors from the reference position ( $_{ref}f$ ) to the instantaneous position ( $f$ ) is computed:

$$R = f \cdot f_{ref}^T$$

For each rotation matrix ( $R$ ), the corresponding rotation vector ( $\mathbf{r}$ ) is extracted:

$$\mathbf{r} = \begin{pmatrix} r_x \\ r_y \\ r_z \end{pmatrix} = \begin{pmatrix} R_{32} - R_{23} \\ R_{13} - R_{31} \\ R_{21} - R_{12} \end{pmatrix} \div (1 + R_{11} + R_{22} + R_{33})$$

### APPENDIX III

The horizontal ( $b$ ) and vertical ( $v$ ) direction of gaze of a rotation vector ( $\mathbf{r}$ ) in degrees are computed according to Haustein<sup>21</sup>:

$$b = \frac{360}{\pi} \cdot \text{atan} \left( \frac{(-r_z - r_x r_y)}{(1 + r_x^2)} \right) \quad v = \frac{360}{\pi} \cdot \text{atan} \left( \frac{-r_y + r_x r_z}{(1 + r_x^2)} \right)$$

Cyclotorsion ( $t$ ) in degrees is given by:

$$t = \frac{360}{\pi} \cdot \text{atan}(r_x)$$