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Analysis of eye movements during myopic laser in situ keratomileusis

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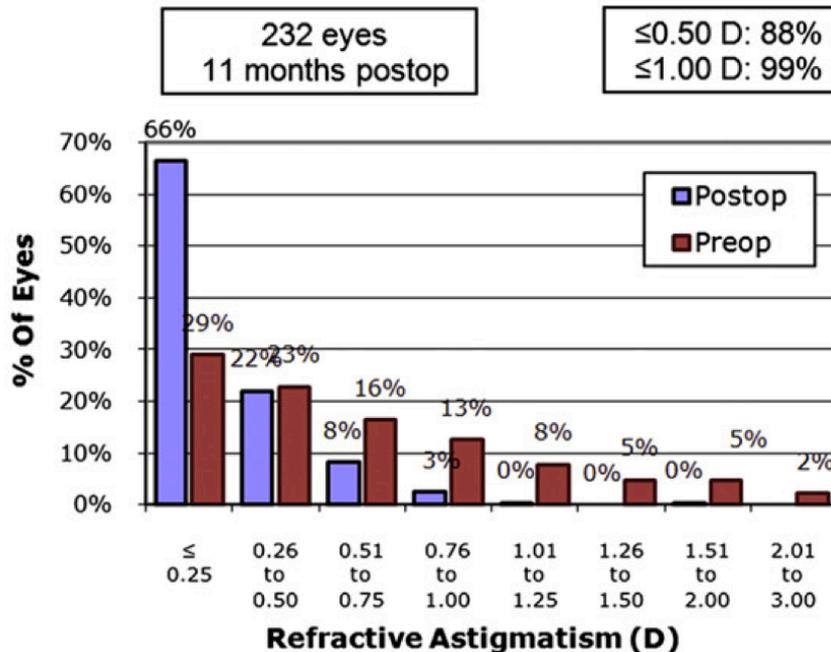


Coauthors

- Eva Rausch
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- Marcus Honig
- Jens Bühren
- Oliver Klaproth

Outcome evaluation in refractive surgery

Safety	Efficacy	Predictability	Stability	Complications
<ul style="list-style-type: none"> Gain and loss of UDVA and CDVA 	<ul style="list-style-type: none"> % of eyes within certain VA thresholds (SPH + CYL) 	<ul style="list-style-type: none"> Achieved vs. attempted 	<ul style="list-style-type: none"> Development over time 	<ul style="list-style-type: none"> Over- or under correction Intra- and postoperative complications



Dupps WJ, Jr., Kohnen T, Mamalis N, Rosen ES, Koch DD, Obstbaum SA, et al. Standardized graphs and terms for refractive surgery results. J Cataract Refract Surg 2010;37:1-3.

Outcome evaluation in refractive surgery

Safety

- Gain and loss of UDVA and CDVA

Efficacy

- % of eyes within certain VA thresholds
- (SPH + CYL)

Predictability

- Achieved vs. attempted

Stability

- Development over time

Complications

- Over- or under correction
- Intra- and postoperative complications

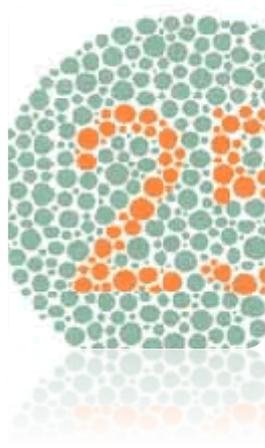
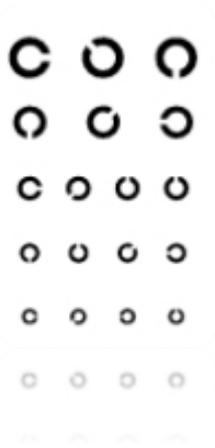


Quality of vision

- Night vision, glare disability, contrast sensitivity
- Higher order aberrations
- Subjective satisfaction

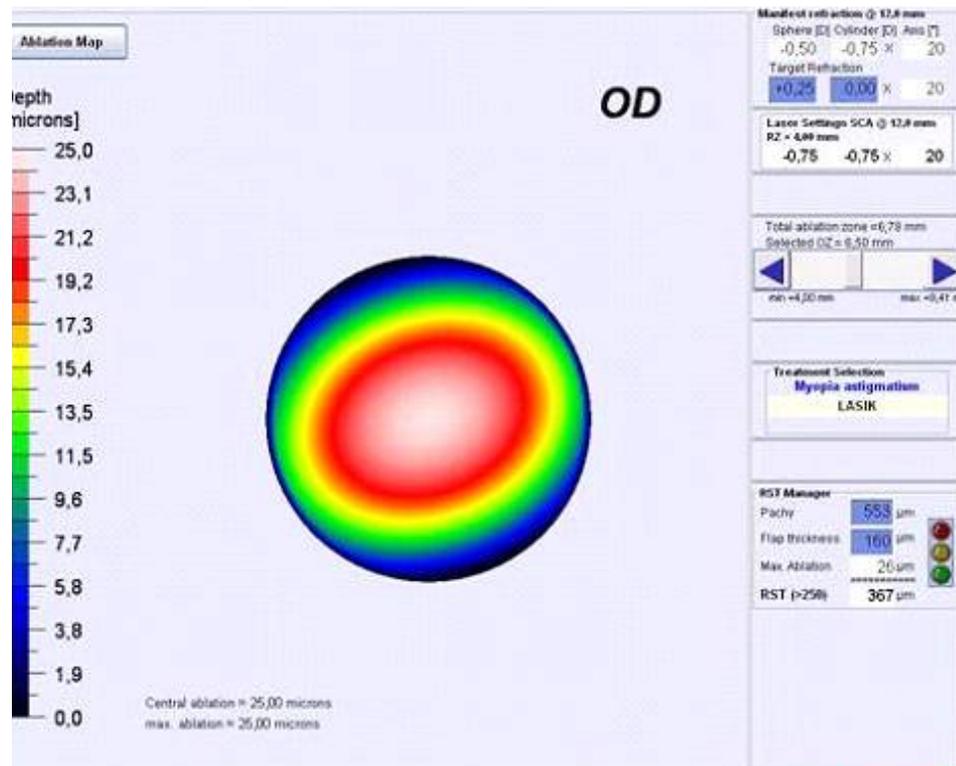
Quality of Vision (QoV)

- Requires precise ablation, according to optical requirements of individual patients
 - surrounding conditions
 - physiological and anatomic conditions



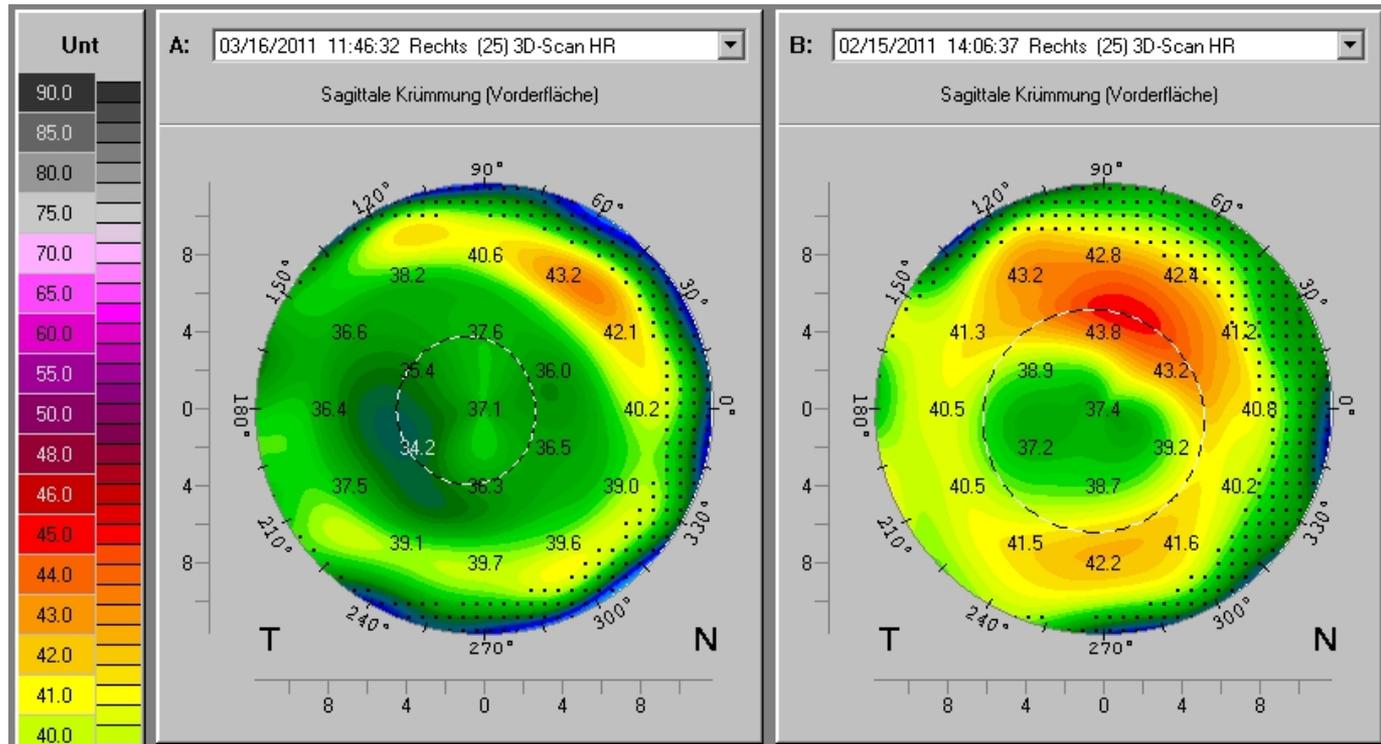
Aspheric treatment profile

- Based on manifest refraction (lower order aberrations) only
- Goal: To maintain ocular aberrations
- Normal cornea, virgin eyes, good QoV, little HOA (RMS <math><0.3\mu\text{m}</math>)



Corneal Wavefront ablation

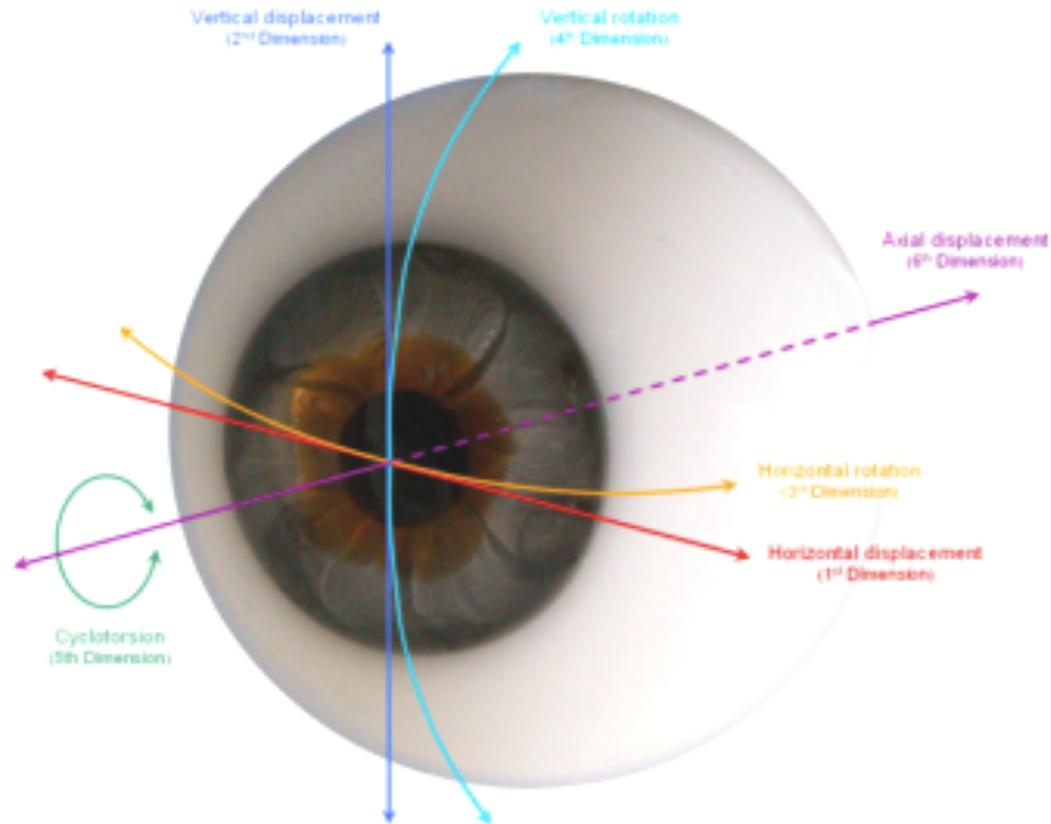
- Precise local spot positioning important for:
 - correction of local irregularities
 - enlargement of optical zones



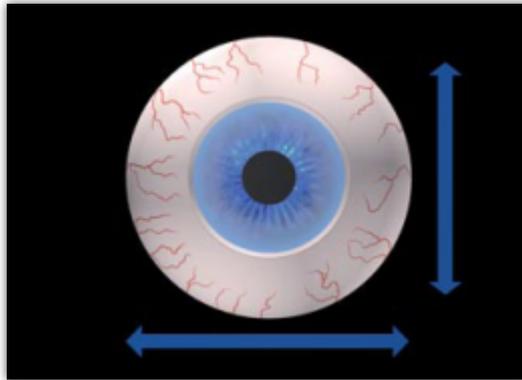
post

pre

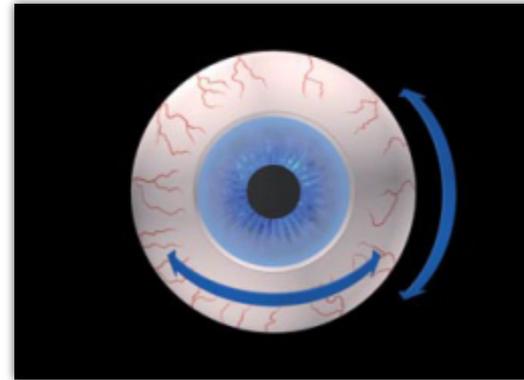
Dynamic eye movements – 6D



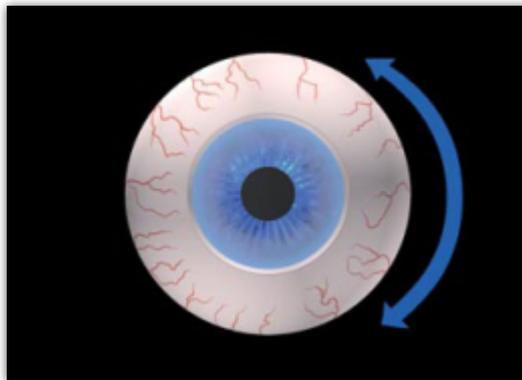
Dynamic eye movements – 6D



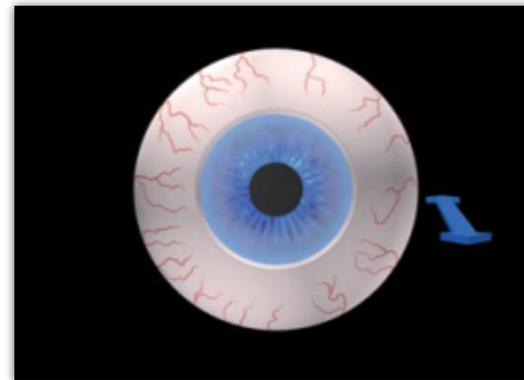
Linear movements (1st and 2nd dimensions)



Rolling movements (3rd and 4th dimensions)



Cyclotorsion (5th dimension)

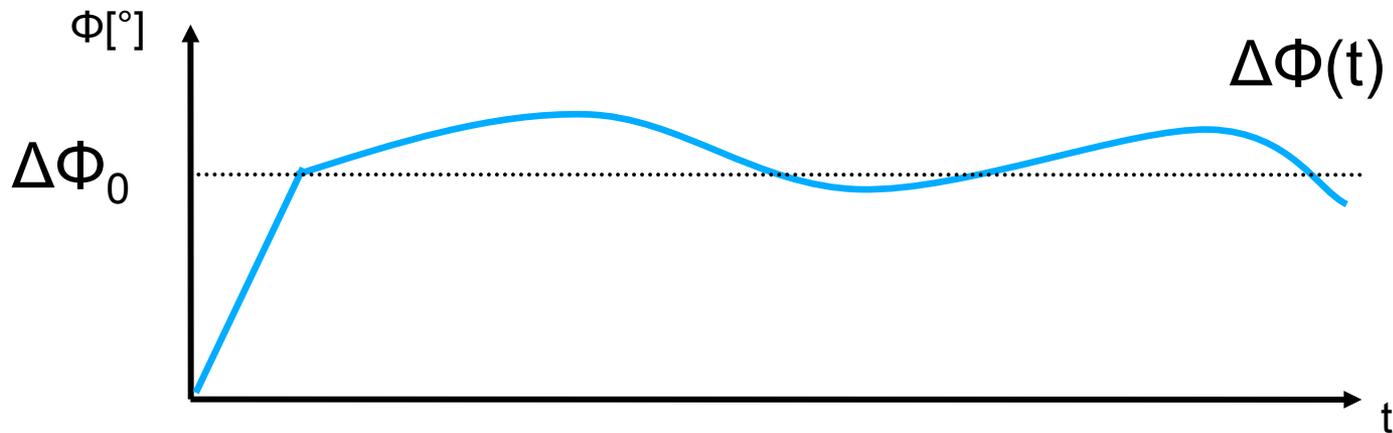


Movements along the z-axis (6th dimension)

Cyclotorsion

dynamic:

- intraoperative cyclotorsion related to supine position



Trial

- 409 / 279 myopic eyes (static / dynamic)
- Myopic LASIK
- ACE 100 eye tracker, Technolas Perfect Vision, München, Germany
- Analysis of magnitude, direction and frequency of cyclotorsion

Background

Ocular cyclorotations are clinically classified in two different components. Static cyclorotation, induced by changing patients from seated position at diagnostic instruments to supine position or by head movements when changing patients position while surgery. Dynamic rotations are rotational arbitrary or automatic eye movements, classified by their amplitude and frequency in change of direction. [1,2] Those rotations might cause imprecise laser spot alignment and thus worsen the visual outcome by increasing corneal lower and higher order aberrations. [3,4]

Purpose

To describe the magnitude, direction and frequency spectra of cyclorotational eye movements in LASIK.

Methods

Analysis of pre-operative and intra-operative cyclorotation of 409 and 279 eyes, respectively that underwent myopic laser in situ keratomileusis with a dynamic iris recognition enabled eye tracker.

Static measurement

pre-operative measurement of static cyclorotation was performed non-invasively in the seated position at the Zyoptix™ diagnostic workstation (Technolas Perfect Vision, Munich, Germany) and at the time of surgery with the eye tracker integrated in the excimer laser in the supine position. Iris images were taken at the diagnostic workstation and compared to those taken at the laser to detect static cyclorotation.

Calculation of astigmatic under-correction

From the known values of attempted astigmatism correction (c) and measured static cyclorotation ($\Delta\Phi_c$) the theoretical postoperative astigmatic under-correction c, was calculated ($c = 2 \sin\Delta\Phi_c \cdot c$). [2]

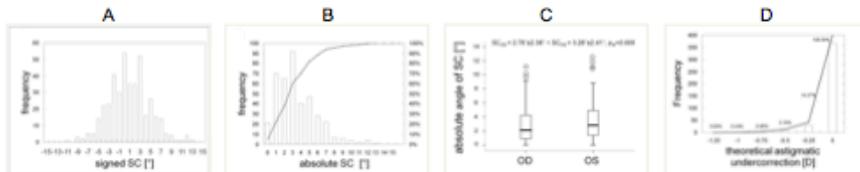
Dynamic measurement

The intra-operative dynamic cyclorotation tracking system is working with a repetition rate of 25 Hz, the laser itself with 100 Hz. Thus, every fourth laser spot is aligned by the eye tracker and was used for the analysis of movements. The analysis of the rotational movements of the laser with 25 Hz indirectly reflects the rotational movements of the eye.

Fourier Analysis

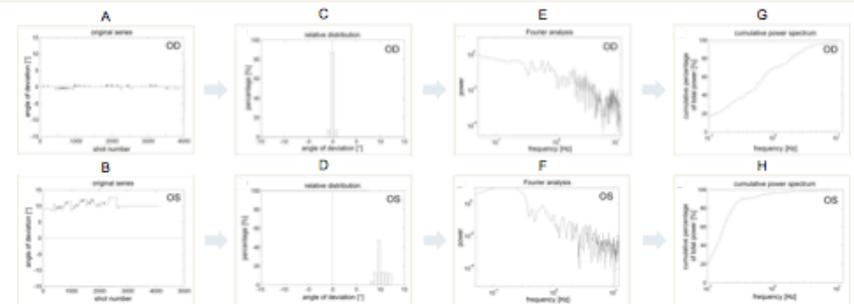
Using a custom-written MATLAB program (MATLAB 7.0; The MathWorks Inc., Natick, Mass., USA), temporal power spectra of dynamic cyclorotation were calculated by the laser movements to determine the frequency below which the majority of rotational eye movements occurred. The temporal power spectrum is a simple way to quantify the size of eye movements as a function of frequency. [2] Fast eye movements are represented by high temporal frequencies, slow movements by low temporal frequencies. Small-amplitude movements have a low power and large-amplitude movements a larger power, respectively. [2] In this trial, a 95% threshold has been chosen as criterion (f95) to define the majority of eye movements.

Results: pre-operative static rotation



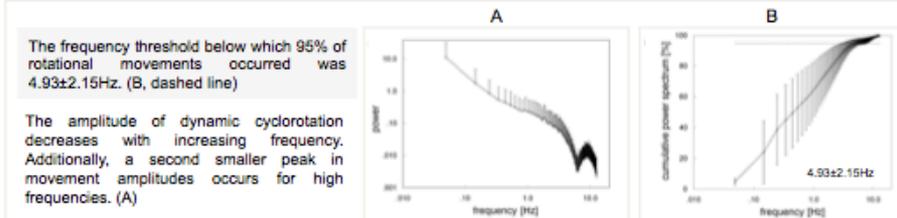
Analysis of static cyclorotation. Induced by changing from seated to supine position and inter-procedure head movements. Relative frequency of pre-operative static cyclorotation (SC). A: Signed values. B: Absolute values. C: Amount of absolute static cyclorotation in right and left eyes. D: Cumulative frequencies of theoretical astigmatic under-correction.

Results: intra-operative dynamic rotation



Descriptive analysis of dynamic rotation of the same patient's right and left eye. A and B: real time tracking analysis, dynamic cyclorotation as a function of ablation shots; C and D: Relative distribution of dynamic cyclorotation. E and F: Fourier analysis, temporal power spectra; G and H: Fourier analysis, cumulative power spectra.

This patient displayed large inter-eye differences. The left eye shows more high-power movements. (A, B, E, F) The low-power movements superimposing the high power movements are similar in both eyes. (A, B, E, F) In the patient's left eye, low-frequency (and thus high-power) movements take larger percentage of all dynamic cyclorotation than in the right eye, where the high-frequency (and thus low-power) movements dominate. (G, H) The cumulative percentage increases with higher slope in the left eye compared to the right eye. (G, H)



Conclusions

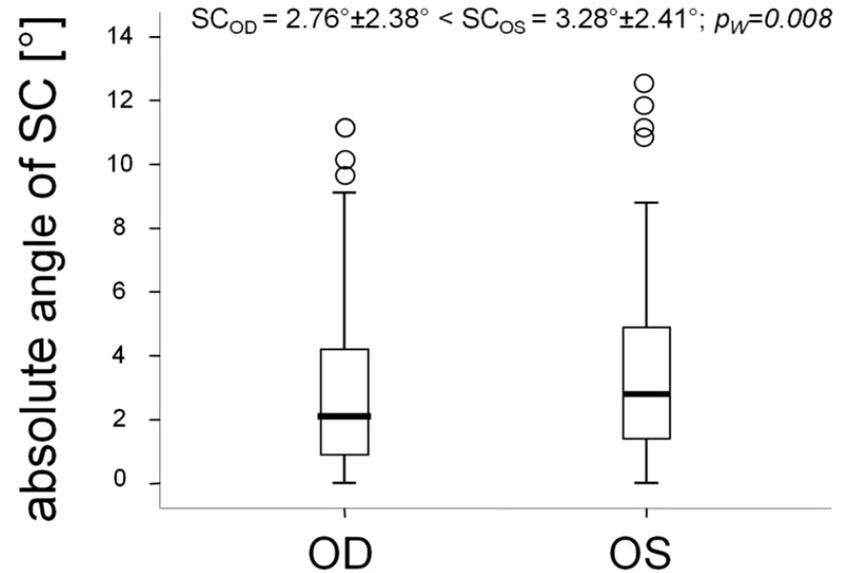
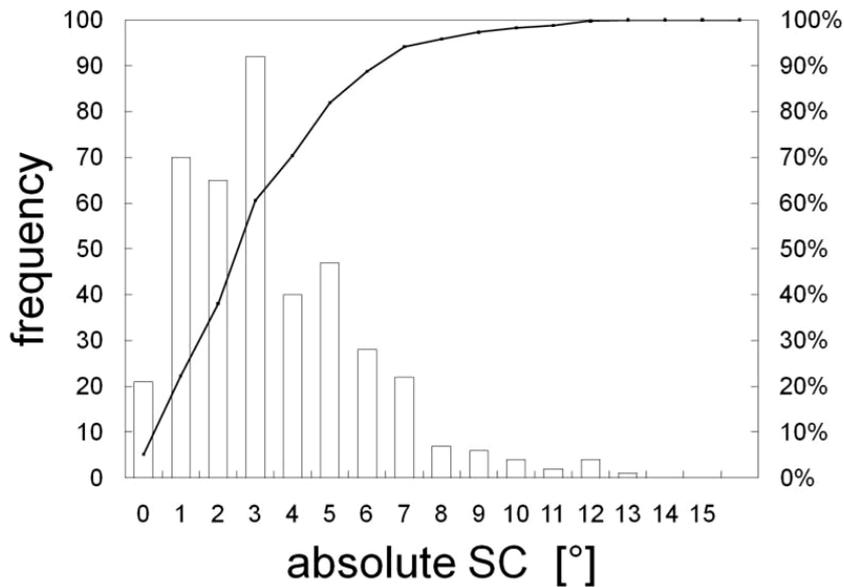
- Only in very few cases static cyclorotation causes clinical significant astigmatic under-correction $\geq 0.75D$.
- Dynamic rotational ocular movements are dominated by low-frequency, high-power cyclorotations.
- Under surgical conditions ocular cyclorotation might reach orders of magnitude that are relevant for the precision of laser refractive surgery.

References

- [1] Kohnen T, Kihne C, Cichocki M, Strenger A. [Cyclorotation of the eye in wavefront-guided LASIK using a static eye tracker with iris recognition] Ophthalmologie. 2007;114:63-5
- [2] Puriar J, Yoon G, MacRae S, et al. Surgeon effects and dynamic eye movements in laser refractive surgery. JCRS 2005;31:2096-2098.
- [3] Alba-Montes R, Menigo-Lopez J, de Ojeda D. Clinical effects of pure cyclorotational errors during refractive surgery. Invest Ophthalmol Vis Sci. 2008;49:4829-4836
- [4] Wang L, Koch DD. Residual higher-order aberrations caused by clinically measured cyclorotational misalignment or decentration during wavefront-guided excimer laser corneal ablation. JCRS 2008;34:2057-2062.

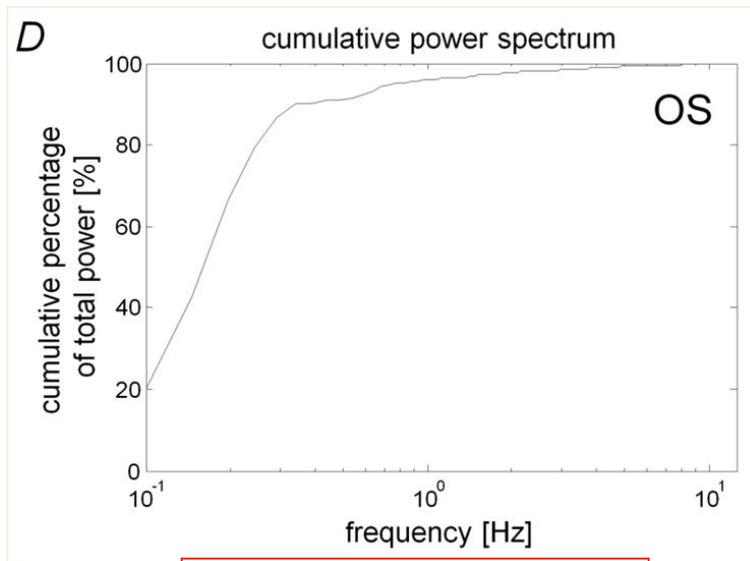
Results

- Mean static deviation: $3.01^\circ \pm 2.41^\circ$
- Range: 0° to 12.3°

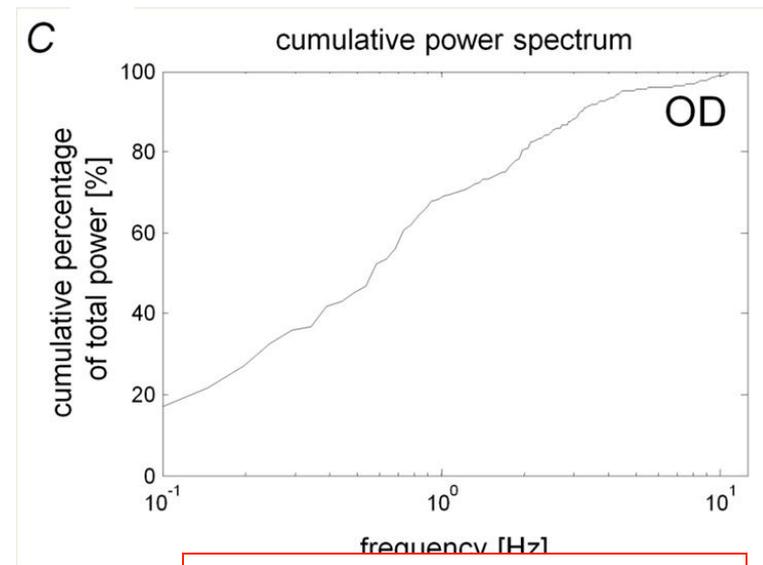


Results

- Mean dynamic deviation: $6.62^\circ \pm 3.33^\circ$
- Range: 0° - 16.25°
- Mean f95 threshold : 4.93 ± 2.15 Hz (0.44 to 9.23 Hz)

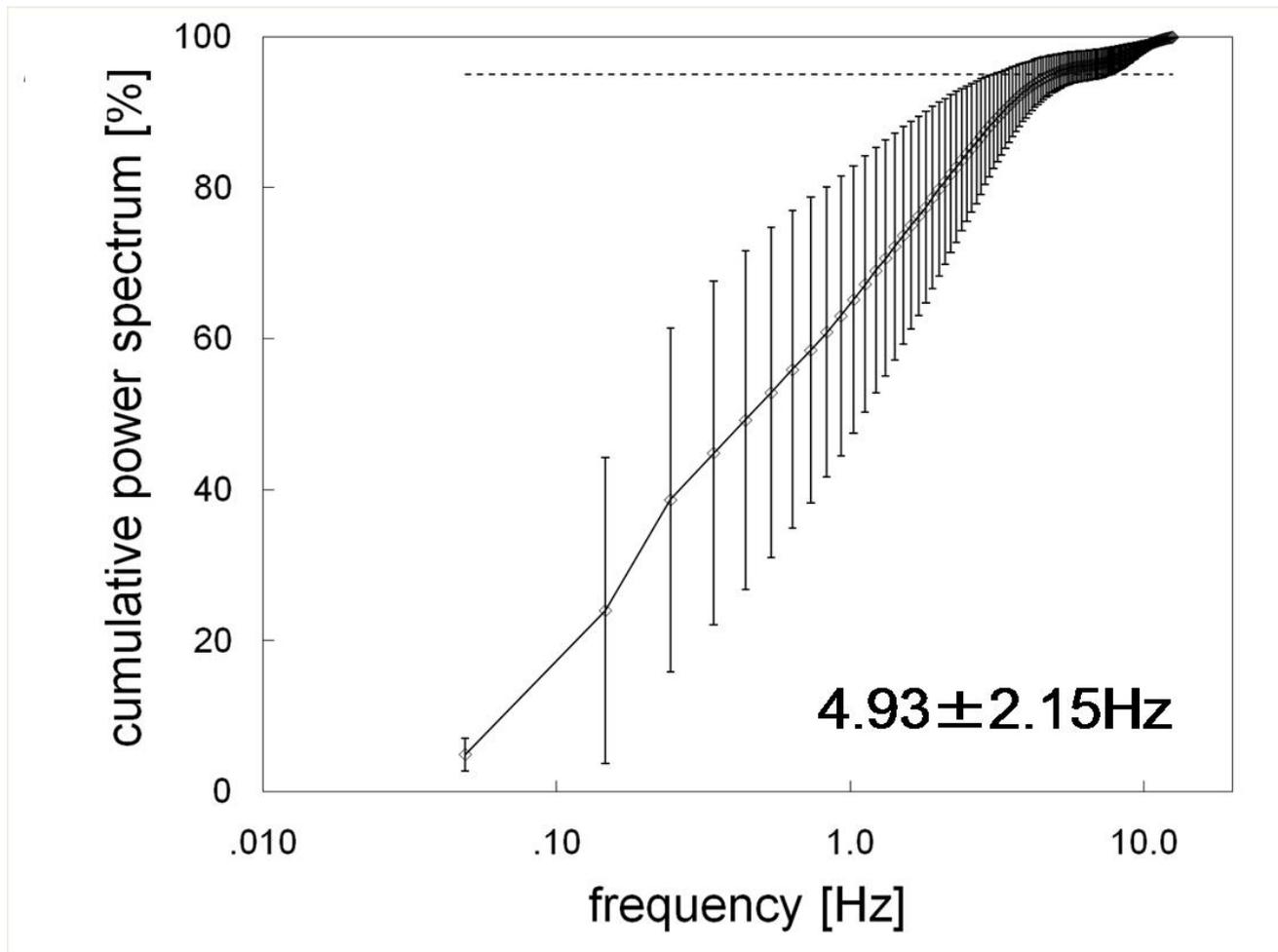


Frequency ↓, Amplitude ↑



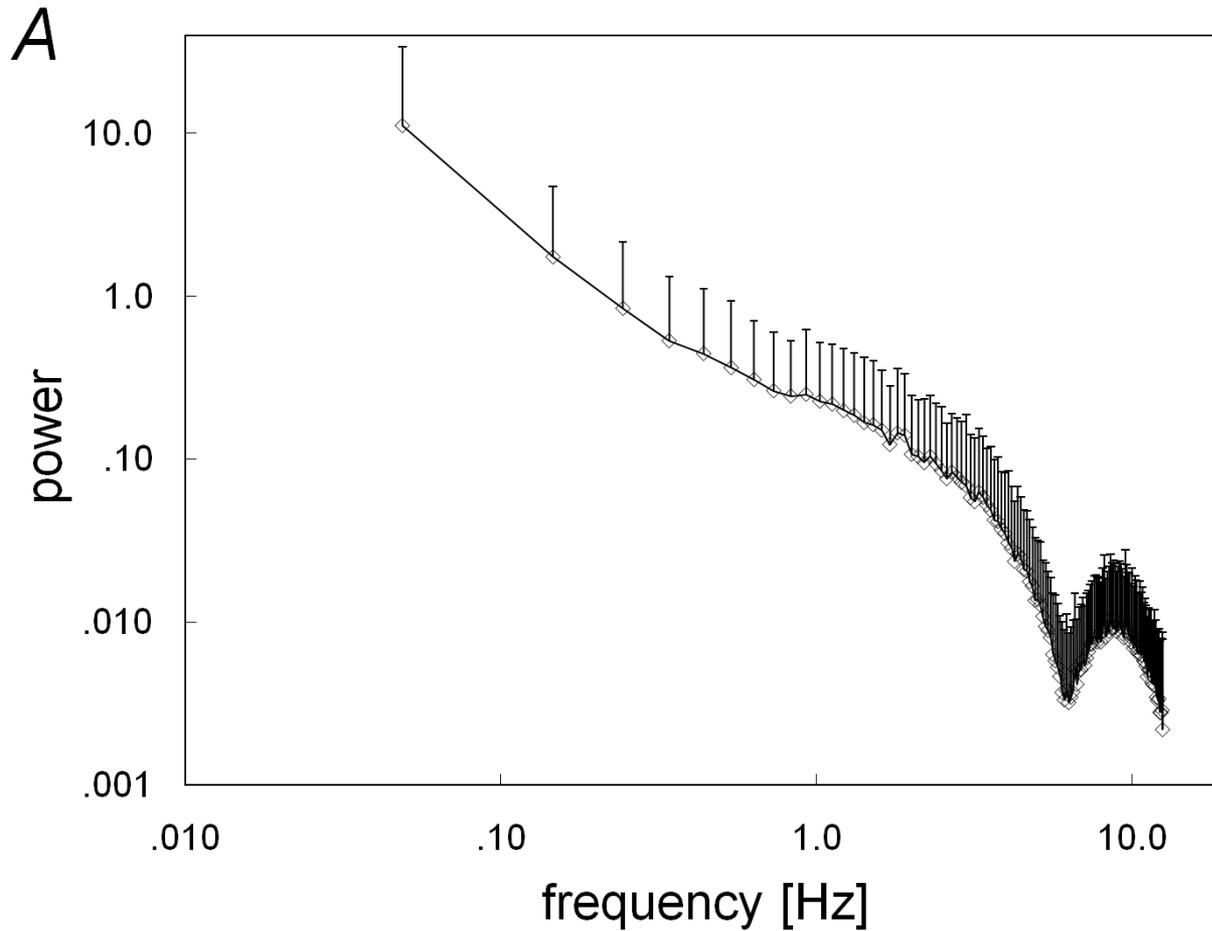
Frequency ↑, Amplitude ↓

Results



Threshold, beneath which 95% of movements occur: $4.93 \pm 2.15 \text{ Hz}$

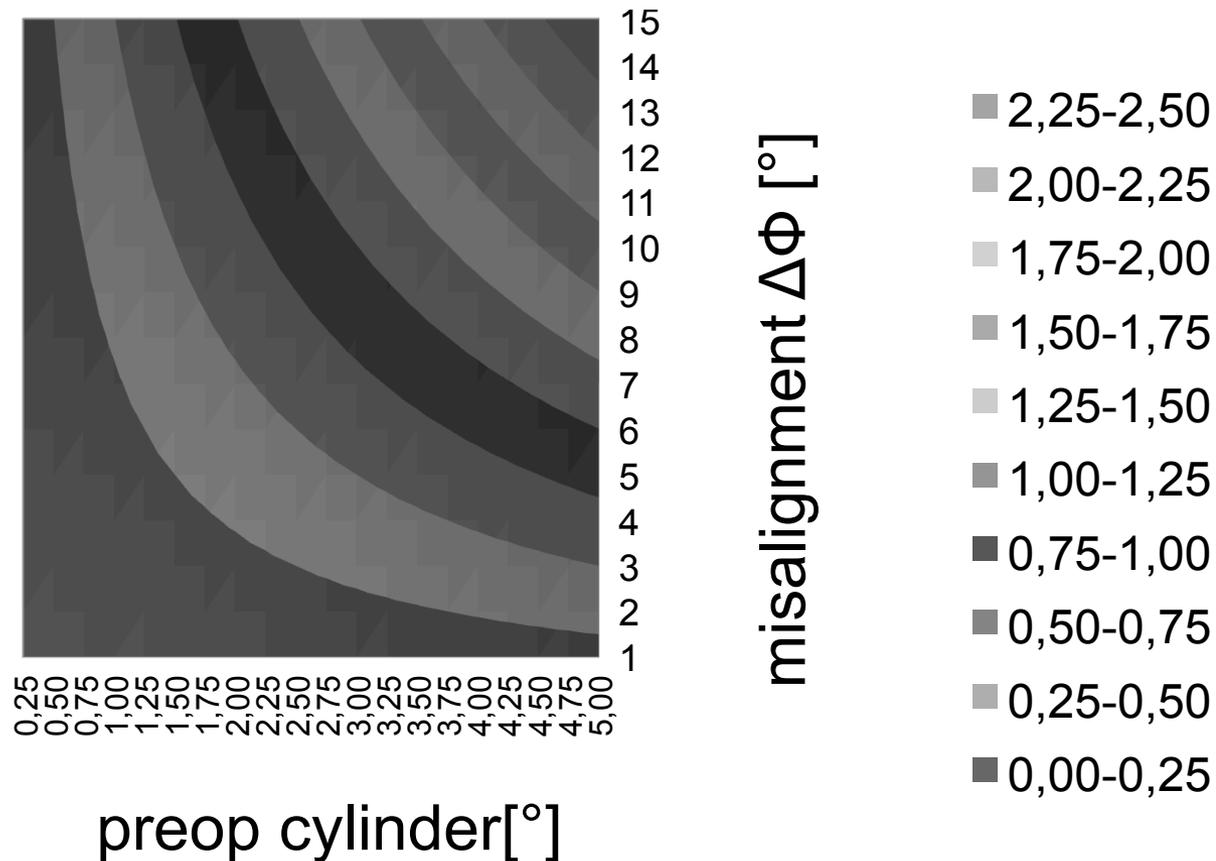
Results



Amplitude decreases with increasing frequency

Influence of static rotational misalignment, theory

- Influence mainly on astigmatism, depending on:
 - Misalignment
 - Magnitude of astigmatism



Influence of dynamic rotational misalignment

- The theoretical impact of cyclotorted ablations is smaller than that of
 - decentered ablations
 - or edge effects in coma and spherical aberrations

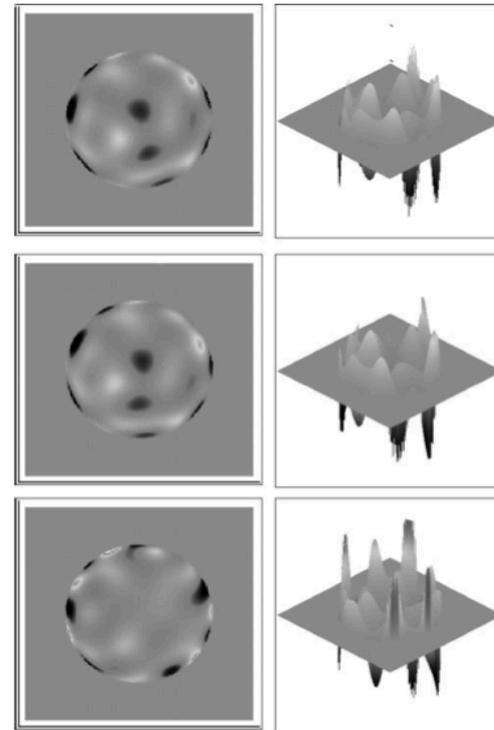


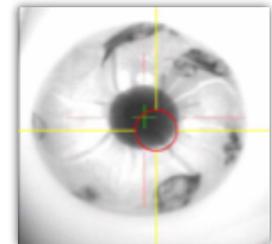
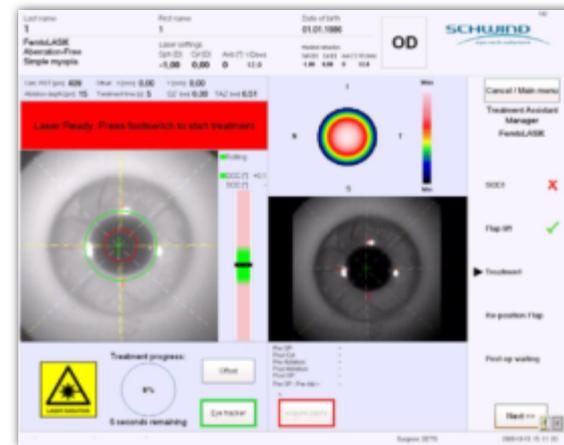
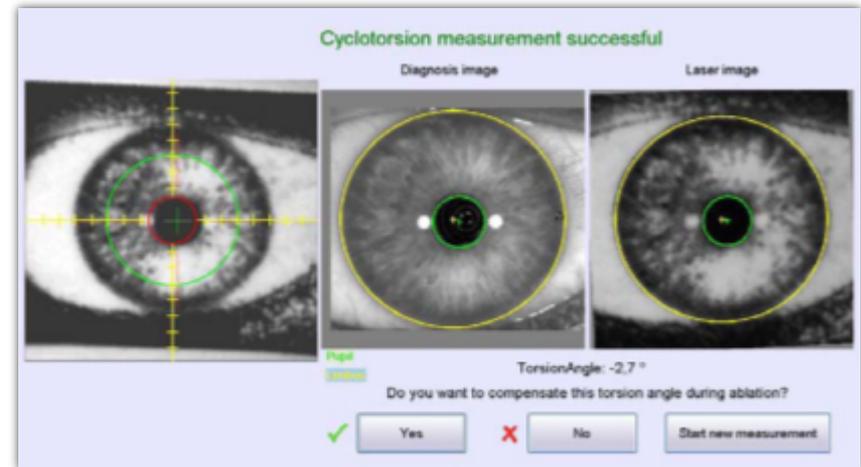
FIGURE 1. *Top:* Original wavefront error; *middle:* 15° clockwise tortured wavefront error; *bottom:* residual wavefront error (all in two dimension and three dimensions).

Factors influencing rotational eye movements

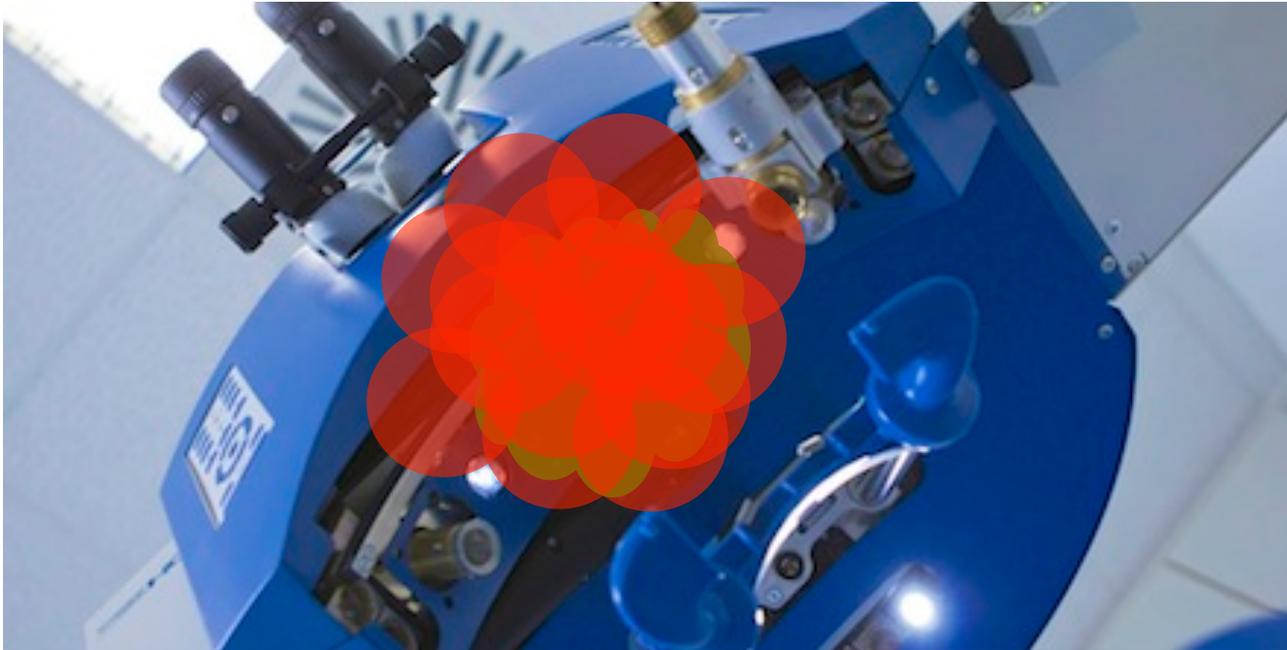
- Position
 - Fixation
 - Stress during measurement
 - Monocular occlusion
 - ... and more
-
- Reliability and repeatability of eyetrackers

Advanced Cyclotorsion Control

- compensates for torsional differences in eye positions between a patient in **upright** and **supine position**.
- compensates for the **torsional movements** of the eye even during laser treatment.
- Adjust the pupil size** with visible light to match the pupil size of the diagnosis reference
 - Better centration of the ablation pattern
 - Less induced aberrations



Our interest



Trial: Purpose

- To evaluate the influence of
 - blur
 - accommodation
 - target laser settings
- on eye movements during laser in situ keratomileusis (LASIK)

Inclusion

- 11 subjects (11 eyes)
- 18 - 41 years
- signed ethic committee-approved written consent

- myopia up to 5 D
- soft contact lens wear

Setup: Simulated treatment

- Amaris 500 Hz excimer laser (Schwind, Germany)
 - 1050 Hz lateral pupil recognition eyetracker
 - 30 Hz torsional, iris and limbus-recognition eyetracker

- Simulation of four treatments on each subject
 - Topical anaesthesia / artificial tears
 - Patients unaware of trial goals



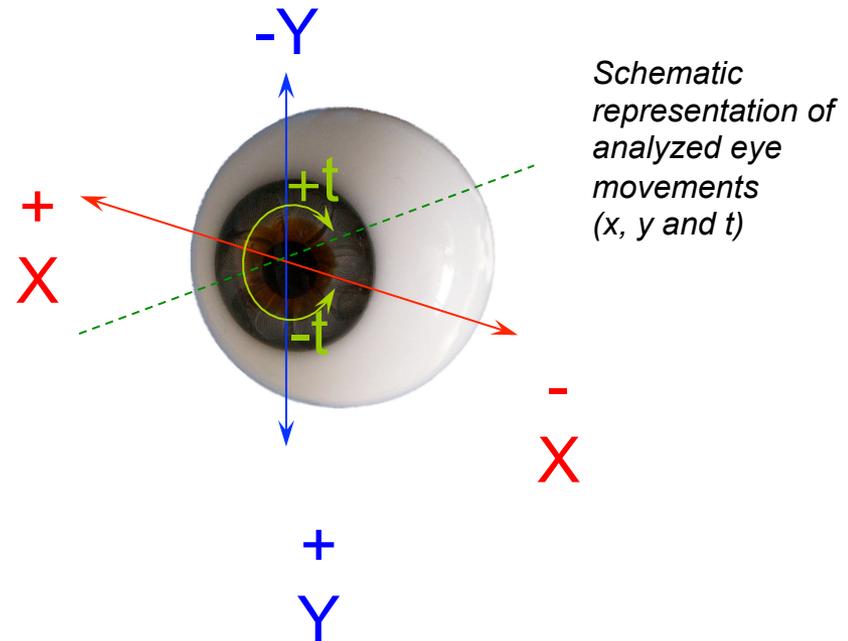
Setup: Simulated treatment

- Two soft contact lenses (CL) (Pure Vision, B+L, USA) per subject
 - one correcting for ametropia
 - one correcting additionally for fixation laser distance to avoid accommodation
- The first CL was “treated” -5D / 7mm optical zone to simulate a LASIK interface.
- Simulated treatments with both CL were performed with
 - target laser on
 - target laser off

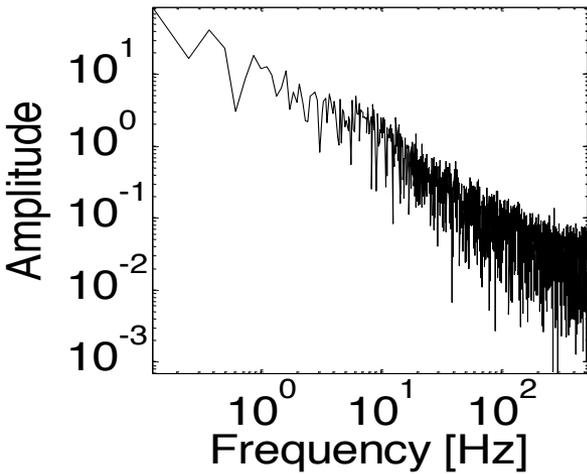
	<i>Target laser on</i>	<i>Target laser off</i>
<i>Simulated interface soft contact lens</i>	Modality 1	Modality 2
<i>Clear soft contact lens (+3 D addition)</i>	Modality 3	Modality 4

Indicators of eye movement

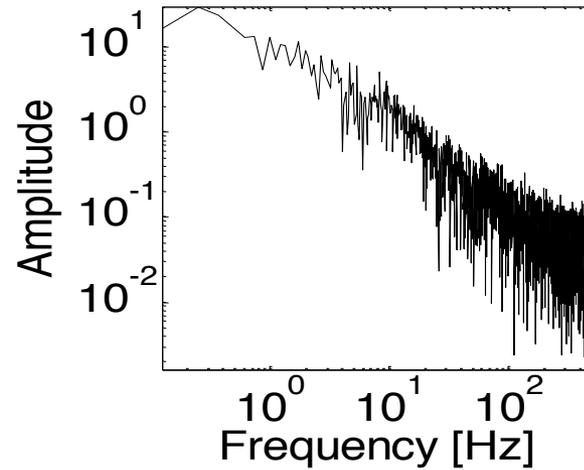
- Custom-written MATLAB Program (The Mathworks, USA)
- **means and standard deviations** of lateral (μm) and torsional [$^{\circ}$] eye movements
- **cumulative x-y translation** [μm] of the pupil
- **FOURIER analysis**
 - frequencies and amplitudes of lateral and torsional eye movements
 - **f95 threshold frequency** [Hz] was defined as the frequency below which 95 % of the respective movements occurred
 - Nyquist Shannon criterion was respected



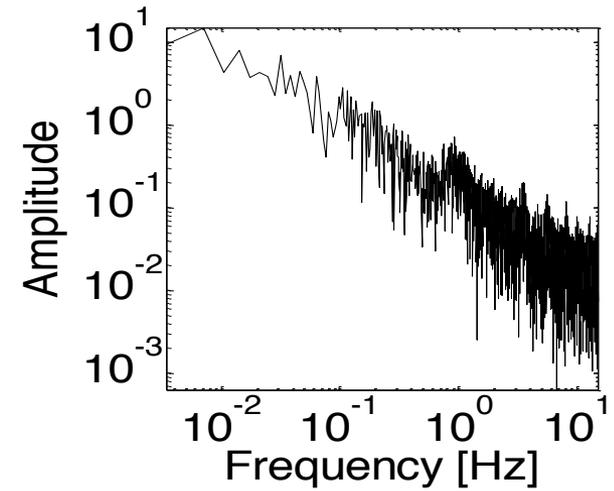
Exemplary power spectra (modality 1)



Lateral x (525 Hz)

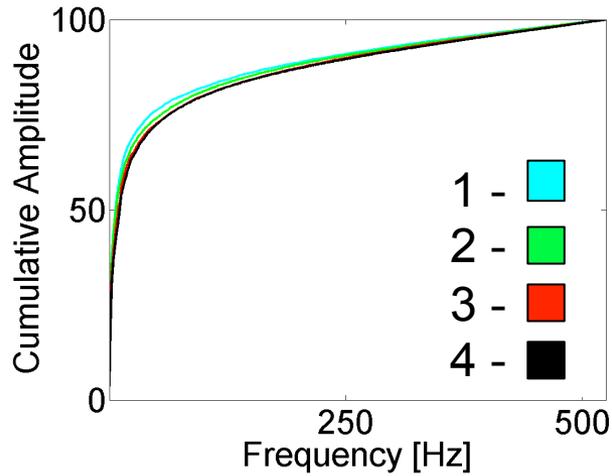


Lateral y (525 Hz)

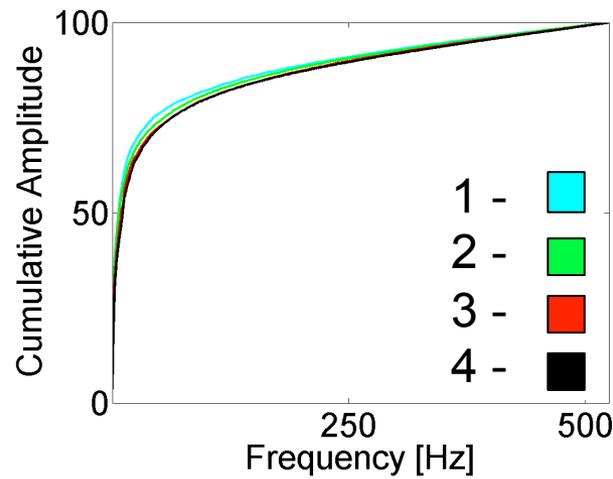


Torsional t (15 Hz)

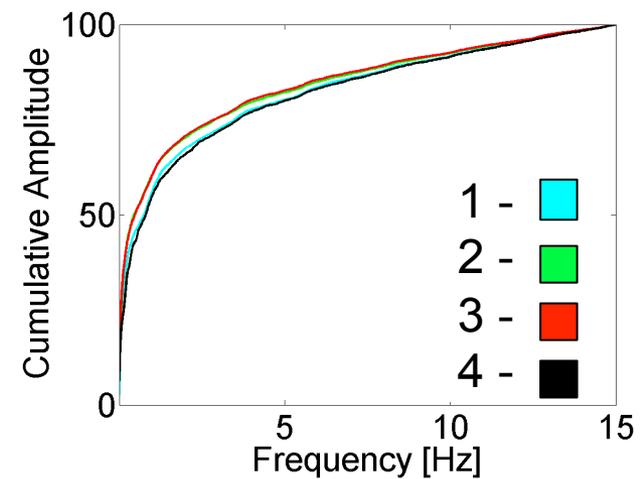
Cumulative power spectra for all 4 modalities



Lateral x (525 Hz)



Lateral y (525 Hz)



Torsional t (15 Hz)

Results

	<i>Modality 1</i>	<i>Modality 2</i>	<i>Modality 3</i>	<i>Modality 4</i>
<i>Mean x-axis movement [μm]</i>	0.62	0.66	0.62	0.53
<i>Mean x-axis movement, standard deviation [μm]</i>	8.78	11.19	10.19	8.86
<i>Mean y-axis movement [μm]</i>	0.77	0.62	0.71	0.50
<i>Mean y-axis movement, standard deviation [μm]</i>	10.73	8.66	12.57	6.52
<i>Mean torsion [$^\circ$]</i>	0.25	0.15	0.14	0.13
<i>Mean torsion, standard deviation [$^\circ$]</i>	2.12	1.67	1.65	1.25
<i>Pupil translation [μm]</i>	61675.36	57152.67	57181.59	55387.58
<i>f95_x [Hz]</i>	327.80	339.75	323.34	342.95
<i>f95_y [Hz]</i>	391.41	399.84	382.90	419.96
<i>f95_{torsion} [Hz]</i>	11.27	11.01	11.03	11.18

No significant differences (Shapiro-Wilk, ANOVA and consecutive Bonferroni post-hoc testing)

Conclusion

influence of blur, accommodation, target laser settings on eye movements during LASIK

- Modification of
 - blur
 - accommodation and
 - target laser settings
- during LASIK

- did not alter intraoperative eye movements.

Conclusion

Analysis of eye movements during myopic laser in situ keratomileusis

- Cyclorotation
 - Static: $3.01^\circ \pm 2.41^\circ$ (range: 0° to 12.3°)
 - Dynamic: $6.62^\circ \pm 3.33^\circ$ (range: 0° - 16.25°)

- Modification of
 - Blur, accommodation and target laser settings did not alter intraoperative eye movements

- The theoretical impact of cyclotorted ablations is smaller than that of
 - decentered ablations
 - or edge effects in coma and spherical aberrations

Thank you for your kind attention!

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