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The Effect of Ocular Rigidity Upon the Characteristics of Saccadic Eye Movements

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PURPOSE. To determine whether variation in ocular rigidity (a quantity that describes the elastic properties of the globe) affects the characteristics of horizontal saccadic eye movements.

METHODS. Thirty-three young, visually healthy subjects participated with informed consent in the study. Axial length was measured using the IOLMaster ocular biometer. Ocular rigidity coefficients were determined using Schiottz tonometry. Horizontal saccades were stimulated randomly to 40° in 10° steps. Eye movements were recorded continuously at a sampling rate of 60 Hz using the Viewpoint video-eyetracker.

RESULTS. Peak velocity increased significantly with increasing ocular rigidity ($F [2,263] = 30.635, P < 0.001$). Time to peak velocity ($F [2,263] = 27.723, P < 0.001$) and total response time ($F [2,263] = 21.133, P < 0.001$) decreased significantly with increasing ocular rigidity. Ocular rigidity was significantly positively correlated with peak velocity ($R^2 = 0.67, P < 0.001$), and significantly negatively correlated with time to peak velocity ($R^2 = 0.64, P < 0.001$), and total response time ($R^2 = 0.62, P < 0.001$).

CONCLUSIONS. The known relationship of ocular rigidity with myopia can be extended to shorter hyperopic eyes, which are found to have higher ocular rigidity. The dynamic characteristics of saccadic eye movements are found to vary systematically with ocular rigidity. These findings suggest that the structural characteristics of the eye are an important factor in determining dynamic characteristics of eye movements.

Keywords: ocular rigidity, axial length, saccadic eye movements, peak velocity

Saccadic eye movements are an integral part of the visuomotor system.¹ Many studies have described the key characteristics of saccadic eye movements such as peak velocity (PV), time to peak velocity (TPV), total response time (TRT), and latency. Peak velocity varies with stimulus size, increasing from 114°/s for a 5° stimulus² to 445°/s for a 20° stimulus,³⁻⁵ and to more than 500°/s for a 30° stimulus.^{4,5} Time to peak velocity varies with stimulus size from 16 ms for a 3° stimulus to 22.5 ms for a 9° stimulus.⁶ Total response time increases with stimulus size from 22 ms for a 4° stimulus⁷ to 68 ms for 10° stimulus and to 91 ms for a 20° stimulus.³ Latency varies from 136 to 275 ms in visually healthy observers depending upon eye recording techniques, experimental design, and age.^{5,8,9}

Refractive error arises primarily as a result of differences in axial length, with shorter axial lengths producing hyperopia,^{10,11} and longer axial lengths leading to myopia.^{10,12-14} Recent work has shown that the increase in ocular size in myopia is found in all planes (Miller JM, et al. *IOVS* 2004:ARVO E-Abstract 2388; Logan NS, et al. *IOVS* 2005: ARVO E-Abstract 4266; and Refs. 12-14), although the enlargement is largest in the axial plane.^{14,15} It is well established that ocular rigidity (OR) is reduced in larger myopic eyes compared with emmetropic¹⁶⁻¹⁹ and hyperopic eyes.^{16,17,20} The low OR found in myopia is associated with weakening and reduced tensile strength of the sclera^{19,21,22} and is due primarily to a thinning of collagen fiber bundles and a reduction in the size of the individual collagen fibrils.^{19,22}

Relatively little work has been done to examine whether these variations in OR influence the dynamic characteristics of saccadic eye movements. Robinson²³ found ocular mass to be negligible in determining saccadic time course as increasing the inertia of the system by 9650% did not affect the time course of saccadic responses. These findings demonstrate that extraocular muscle force can easily overcome the ocular mass and associated inertia by several orders of magnitude. Robinson²³ did not measure OR, so was unable to examine the effect of OR upon saccadic eye movement parameters. A recent study of 40 subjects (20 emmetropes and 20 myopes) found that highly myopic eyes (>6 diopters [D]) showed significantly slower mean velocities (up to 20°/s slower) for 7.5°, 15°, and 22.5° of saccadic eye movement.²⁴ In contrast, Hartwig et al.²⁵ found that myopic subjects (mean spherical equivalent [MSE] ranged from -0.88 to -7.13 D) and emmetropes had similar saccadic eye movement characteristics, although they examined only small 10° movements.

The purpose of the present study is to determine whether a normal population variation in OR can affect the characteristics of saccadic eye movements in both long (myopic) and short (hyperopic) eyes.

MATERIALS AND METHODS

Subjects

Thirty-three visually healthy subjects (19 male and 14 female) participated in the experiment. There were 15 myopic

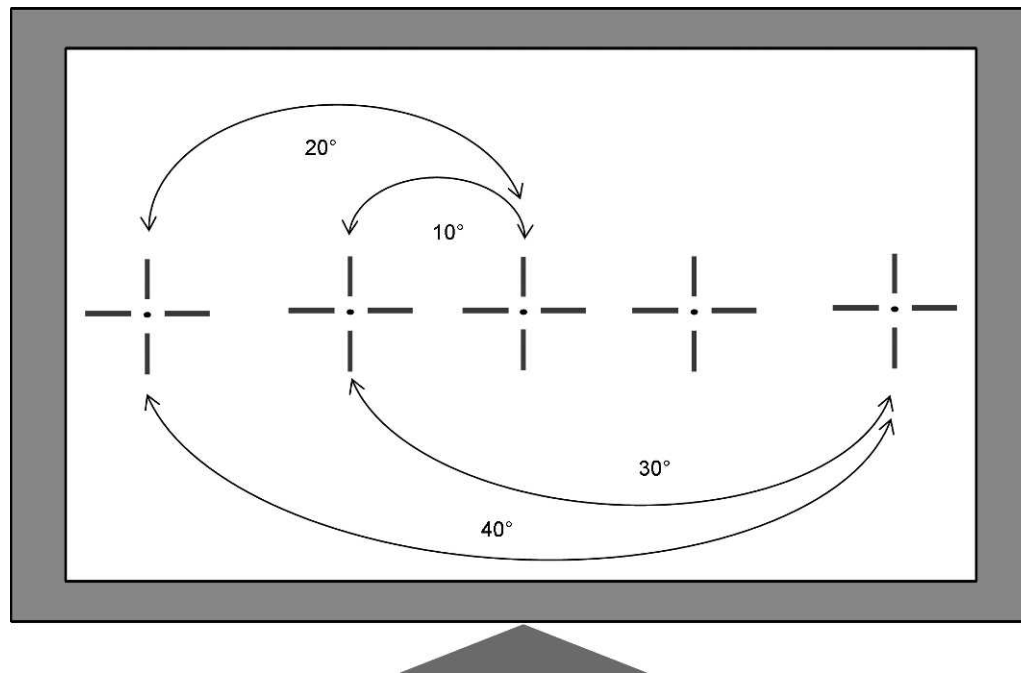


FIGURE 1. The stimulus was composed of a central black dot 0.6° in diameter with surrounding fixation bars 0.4° width, and 3.6° in length. The fixation bars were placed at 0.8° from the central fixation dot. Stimulus displacements were calculated to produce 10°, 20°, 30°, and 40° saccades.

subjects, 10 emmetropic, and 8 hyperopic, ranging in age from 18 to 36 years (mean \pm SD, 23.52 \pm 5.11 years). Ethical approval was obtained from the School of Life Sciences ethics committee and the study was conducted according to the tenets of the Declaration of Helsinki. Informed consent was obtained from each subject prior to beginning the study. Exclusion criteria were any ocular or systemic pathology, including previous history of ocular surgery, history of trauma, ocular or systemic medication, binocular vision abnormality, and astigmatism greater than 2.00 D. Subjects with a range of MSE refractive errors from -10.00 D to $+6.00$ D were recruited to the study.

Visual acuity was fully corrected to 0.0 LogMAR or better with daily disposable soft contact lenses (Focus Dailies, Nelfilcon A [water content 69%]; CIBA VISION, Duluth, GA).

Measurements of Ocular Parameters

Refractive error was measured using standard subjective refraction methods. Axial length was determined by averaging three measurements using noncontact partial coherence interferometry (IOLMaster; Carl Zeiss, London, UK). Intraocular pressure (IOP) was measured using a Schiötz tonometer (Biro Ophthalmic Instruments, Burladingen, Germany) with weights of 5.5, 7.5, and 10 g. Mean IOP values, based on three recordings with each weight, were used to derive OR using Friedenwald's Nomogram.^{26,27} Previous work has shown measurement of IOP using Schiötz tonometry has good repeatability.²⁸⁻³⁰

Stimulus

High contrast (90%) stimuli (Fig. 1) were presented randomly upon a computer monitor (Mitsubishi cathode ray tube, width 49.5 cm, height 49.3 cm, resolution 640 \times 480 at 60 Hz and a brightness of 100 cd/m² for a full white background; Mitsubishi Electric Corporation, Nagasaki, Japan) to elicit saccades of

varying magnitude from 10° to 40° in both rightwards and leftwards directions.

Subjects were aligned centrally to the computer monitor, and the stimuli aligned vertically with the eyes ensuring that only horizontal saccades were elicited. Head movements were restricted by means of a chin and forehead support, with a restraining head strap. The experiment was performed binocularly at a viewing distance of 40 cm.

Stimulus Presentation

For the 10° and 20° saccades, the stimulus was presented randomly at either the primary central position or at 10° and 20° and then moved right or left. For the 30° and 40° saccades the stimulus was presented at 10° and 20° away from the primary position in one direction and then moved in the opposite direction to produce the required stimulus for 30° or 40° (Fig. 1). Stimuli were presented randomly for a minimum of 10 seconds at each location.

Eye Movement Recording

Eye movements were recorded continuously at a sampling rate of 60 Hz using the Viewpoint infrared video eyetracker (Arrington Research, Scottsdale, AZ). This eyetracker has an optimum resolution of 0.15° of visual arc as quoted by the manufacturer. A full examination session lasted 45 minutes and the subjects were given regular breaks to avoid fatigue.

Recordings were rejected where blinks occurred during the response and where latency was shorter than 90 ms or longer than 450 ms as such responses could be due to anticipation or lack of attention, respectively.^{31,32} Every response was repeated 12 times and a minimum of seven clean recordings were averaged for each.

Data Analysis

An algorithm written in MS Visual Basic (Microsoft Corporation, Redmond, WA) was used to detect and remove blinks.

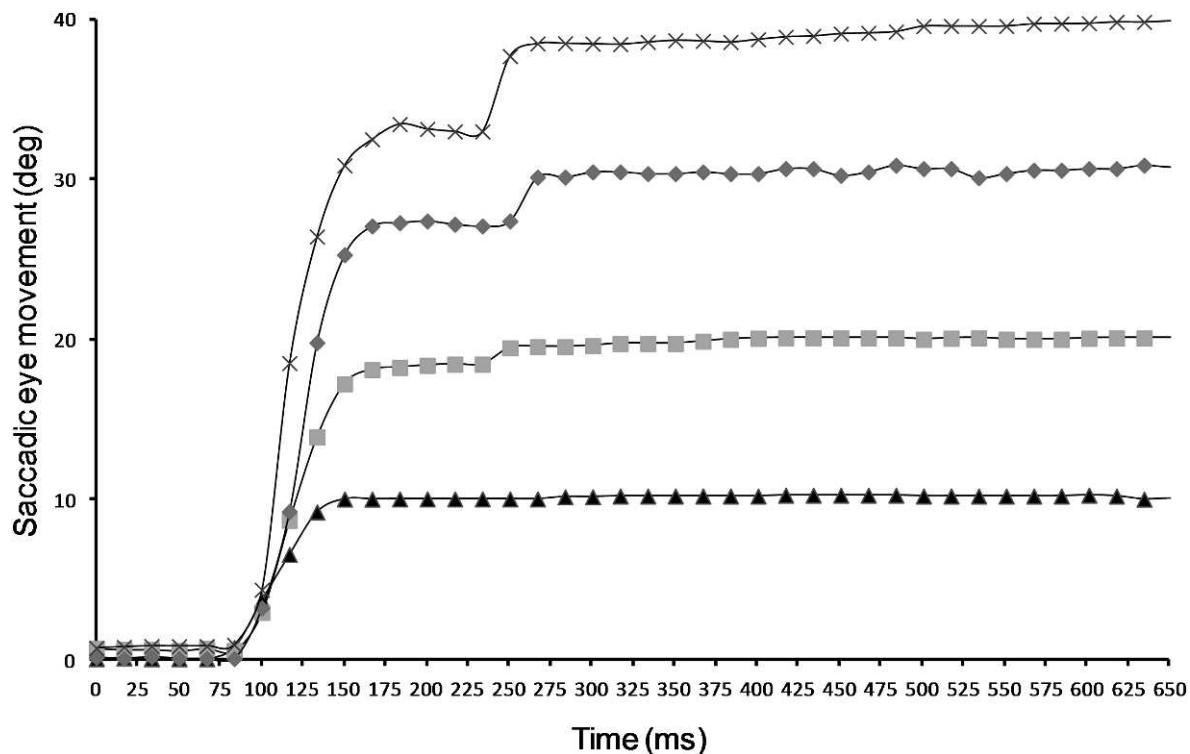


FIGURE 2. Typical saccadic responses for subject SK for 10°, 20°, 30°, and 40° plotted as original eye position against time.

Intersubject variations in interpupillary distance (IPD) were accounted for in the analysis. An example of typical eye movement recordings for one subject is shown in Figure 2.

The following saccadic response characteristics were analyzed offline: PV, TPV, TRT, and latency. Saccadic response onset and completion were determined as the points where eye movement velocity exceeded or fell below 5°/s.^{33,34} The PV was obtained by differentiation of the eye movement recordings after blink removal. Latency was defined as the time between the target onset and the onset of the saccadic response.

Subjects were divided into three arbitrary groups with equal subject numbers according to their OR as follows:

1. High OR (ranged from 0.0175–0.0188 mm Hg/ μ L, mean \pm SD = 0.0182 \pm 0.0004 mm Hg/ μ L): the axial length for this group ranged from 21.31 to 23.29 mm mean \pm SD = 22.73 \pm 0.76 mm;
2. Medium OR (ranged from 0.0148–0.0168 mm Hg/ μ L, mean \pm SD = 0.0157 \pm 0.0006 mm Hg/ μ L): axial length ranged from 23.52 to 24.77 mm, mean \pm SD = 24.00 \pm 0.50 mm; and
3. Low OR (ranged from 0.0132–0.0146 mm Hg/ μ L, mean \pm SD = 0.0142 \pm 0.0009 mm Hg/ μ L): Axial length ranged from 24.82 to 27.76 mm, mean \pm SD = 25.90 \pm 0.93 mm.

All reported data were for the right eye and for centrifugal saccades only. Although the 30° and 40° saccades were crossing the primary position, the eye always landed centrifugally upon the completion of these movements.

Univariate general linear ANOVA was performed on PV, TPV, TRT, and latency with the fixed factors of OR, direction of movement (adduction and abduction), and stimulus size. Post hoc comparisons were carried out using the Tukey HSD test.

RESULTS

Relationship Between OR and Axial Length/Refractive Error

Axial length varied from 21.31 to 27.67 mm (mean \pm SD = 24.21 \pm 1.53 mm). Ocular rigidity and axial length were significantly negatively correlated, ($R^2 = 0.84$, $F [1,32] = 159.080$, $P < 0.001$; Fig. 3). Mean OR for the highest OR group was significantly greater ($F [1,32] = 169.214$, $P < 0.001$) than both the medium OR group ($P < 0.001$) and low OR group ($P < 0.001$), and the medium OR group was significantly greater than the low OR group ($P < 0.001$).

Ocular rigidity and MSE refractive error were significantly positively correlated, ($R^2 = 0.76$, $F [1,32] = 99.058$, $P < 0.001$; Fig. 4).

Peak Velocity

Peak velocity (Fig. 5) increased significantly with increasing OR ($F [2,263] = 30.635$, $P < 0.001$). The high OR group had a significantly faster PV than the medium OR ($P < 0.001$) and the low OR group ($P < 0.001$). The medium OR group showed a significantly faster PV compared with the low OR group ($P = 0.016$). Peak velocity increased significantly with increasing size of saccadic eye movement ($F [3,263] = 711.261$, $P < 0.001$). Peak velocity for 10° was significantly slower than 20°, 30°, and 40° ($P < 0.001$ for all comparisons), 20° was significantly slower than 30° and 40° ($P < 0.001$ for all comparisons) and 30° was significantly slower than 40° ($P < 0.001$). Peak velocity was significantly faster for abductive movements ($F [1,263] = 7.037$, $P = 0.044$). There was an interaction between the factors of stimulus size and OR as the difference in PV between the OR groups increases significantly with increasing stimulus size ($F [6,263] = 2.787$, $P = 0.012$).

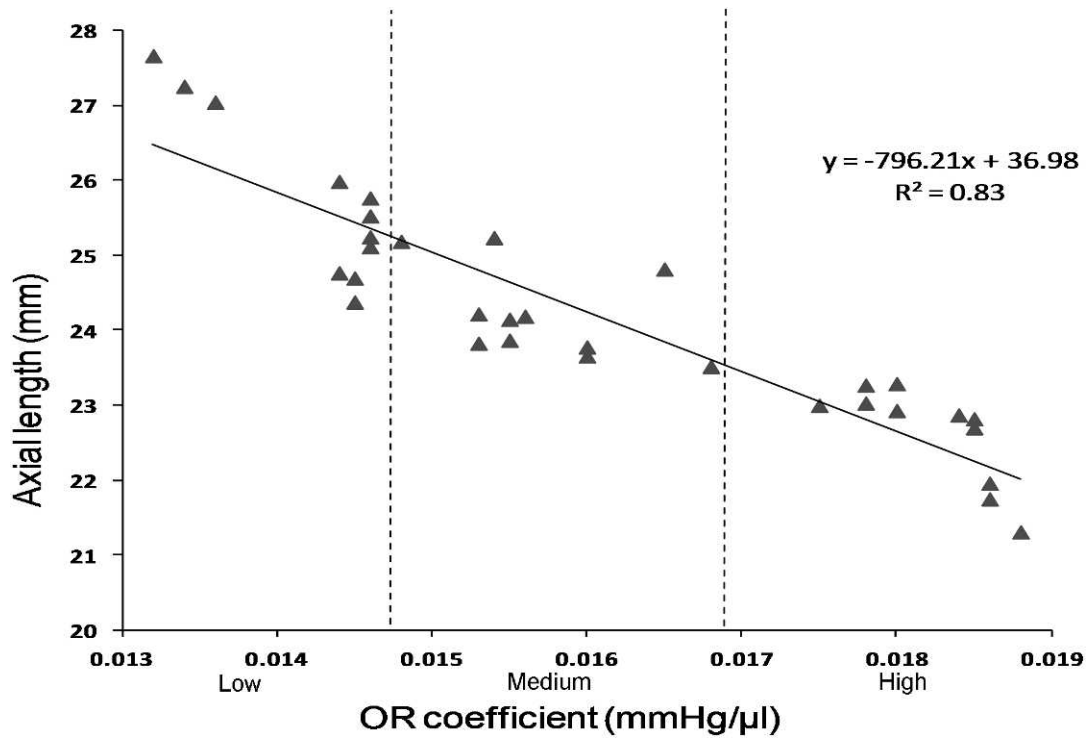


FIGURE 3. The relationship between the axial length and OR.

The asymmetry between abduction and adduction did not vary significantly between the OR groups.

Time to Peak Velocity

Time to peak velocity (Fig. 6) varied significantly between OR groups ($F [2,263] = 27.723, P < 0.001$). The high OR group

had a significantly shorter TPV than the medium OR ($P < 0.001$) and the low OR group ($P < 0.001$). The medium OR group showed a significantly shorter TPV compared with the low OR group ($P = 0.004$). Time to peak velocity was also found to increase significantly with increasing stimulus size ($F [3,263] = 176.974, P < 0.001$). Time to peak velocity was

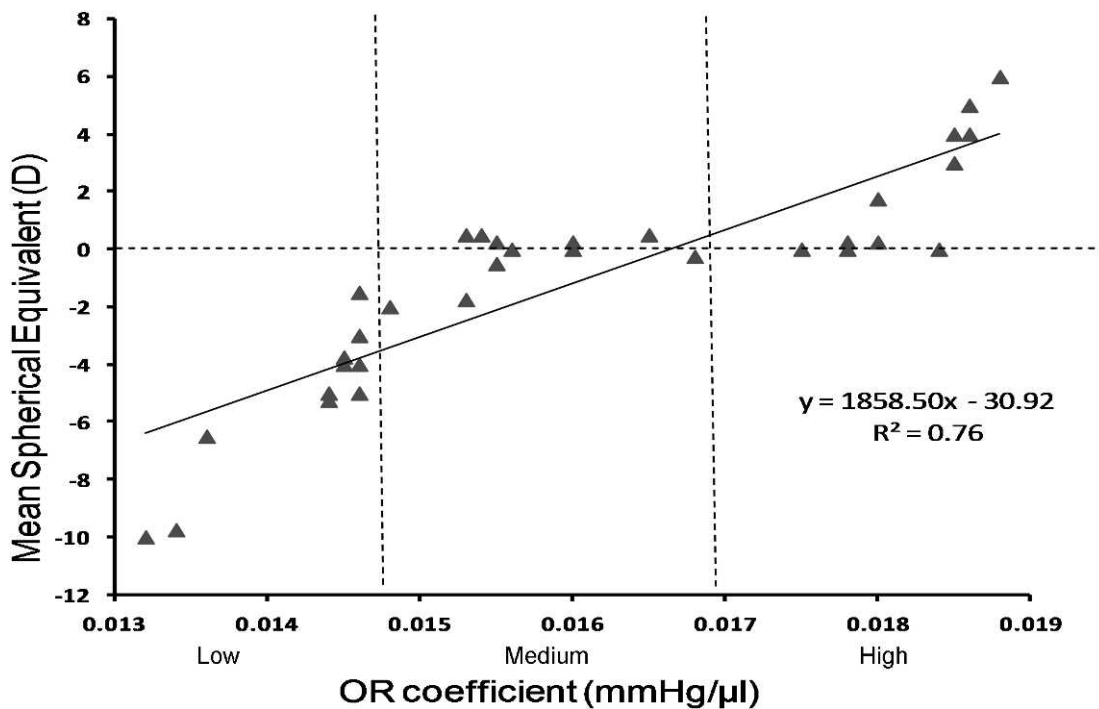


FIGURE 4. The relationship between the MSE and OR.

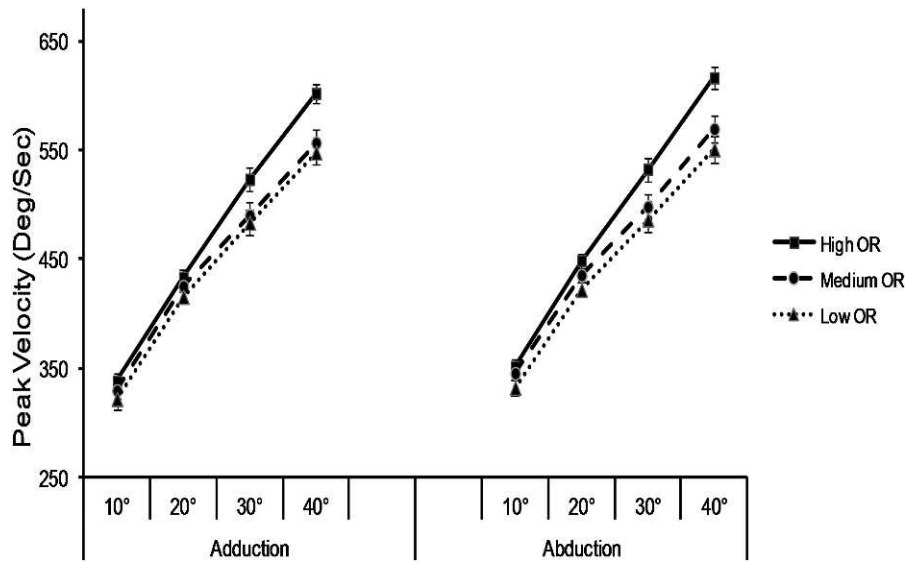


FIGURE 5. Peak velocity for all stimulus sizes in the three subject groups. For clarity, error bars represent the SEM.

significantly shorter for abductive eye movements ($F [1,263] = 13.004, P < 0.001$). There was an interaction between the factors of stimulus size and OR where the difference in TPV between the OR groups increases as the stimulus size increases ($F [6,263] = 3.190, P = 0.005$). The asymmetry between abduction and adduction was not significantly different between the OR groups.

Total Response Time

Total response time (Fig. 7) varied significantly between the OR groups ($F [2,263] = 21.133, P < 0.001$). The high OR group had a significantly shorter TRT than the medium OR ($P < 0.001$) and the low OR group ($P < 0.001$). The medium OR group showed a significantly shorter TRT compared with the low OR group ($P = 0.006$). Total response time was found to be greater with increasing stimulus size ($F [3,263] = 71.553, P < 0.001$). There was an interaction between the factors of stimulus size and OR, as the difference in TRT between the OR

groups increases significantly with increasing the stimulus size ($F [6,263] = 3.368, P = 0.003$). The asymmetry between abduction and adduction was not significantly different between the OR groups.

Latency

No significant variation in latency was found between the OR groups. There was a significant variation in latency with stimulus size ($F [3,263] = 10.522, P < 0.001$) with the 10° response having significantly shorter latency than 20° ($P < 0.001$), 30° ($P = 0.001$), and 40° ($P < 0.001$) responses. No significant difference in latency was found between abductive and adductive eye movements.

Correlation Between OR and PV, TPV, and TRT

Ocular rigidity was linearly correlated with PV, TPV, and TRT for 40° saccadic responses. Ocular rigidity was positively

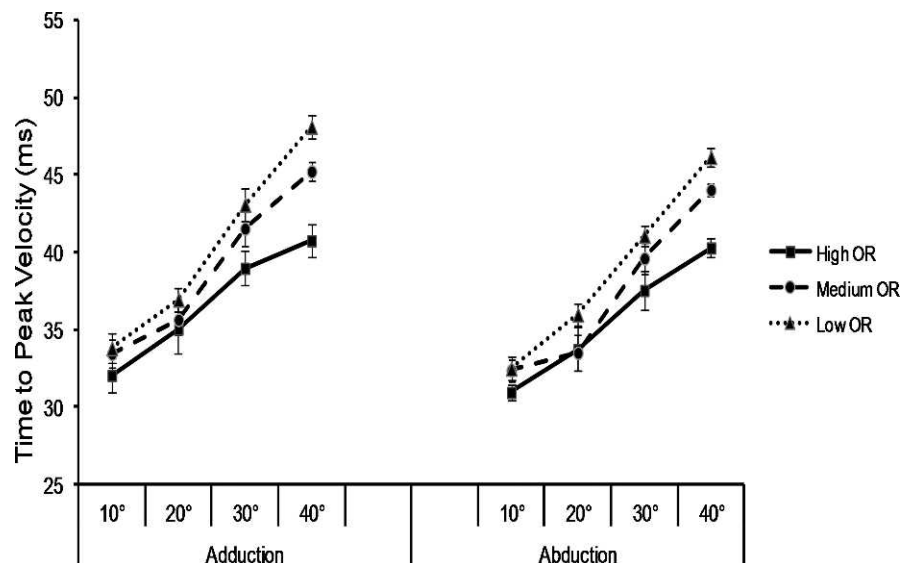


FIGURE 6. Time to peak velocity for all stimulus sizes in the three subject groups. For clarity, error bars represent the SEM.

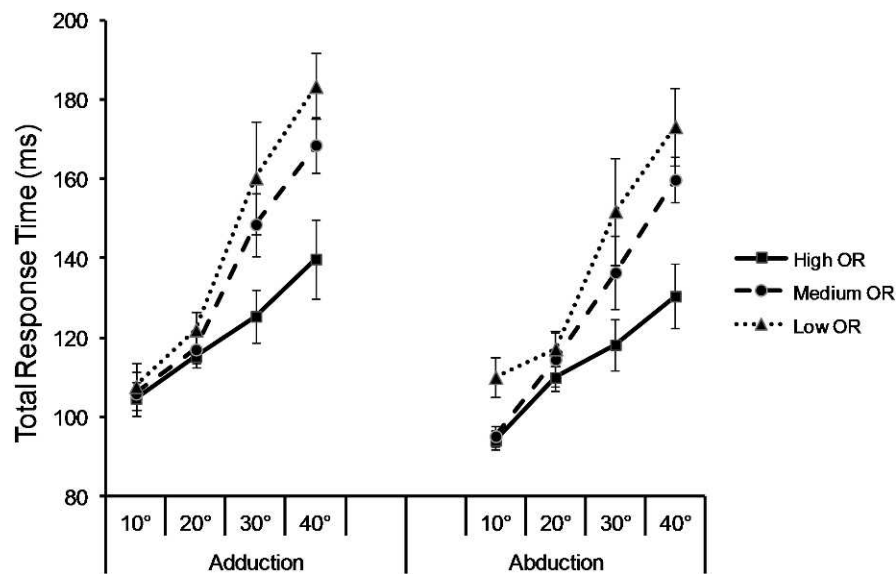


FIGURE 7. Total response time for all stimulus sizes in the three subject groups. For clarity, error bars represent the SEM.

correlated with PV for both abduction ($R^2 = 0.68$, $F = 64.55$, $P < 0.001$, $y = 21565x + 233.12$) and adduction ($R^2 = 0.67$, $F = 62.49$, $P < 0.001$, $y = 19744x + 252.36$) such that eyes with high OR reach higher PV during a saccadic eye movement. Additionally, OR was negatively correlated with TPV for both abduction ($R^2 = 0.64$, $F = 54.22$, $P < 0.001$, $y = -1387.9x + 65.768$) and adduction ($R^2 = 0.70$, $F = 72.89$, $P < 0.001$, $y = -1967.4x + 76.274$). Similarly, OR was negatively correlated with TRT for both abduction ($R^2 = 0.62$, $F = 50.25$, $P < 0.001$, $y = -14117x + 381.1$) and adduction ($R^2 = 0.57$, $F = 37.60$, $P < 0.001$, $y = -12970x + 372.14$).

These correlations between OR and PV and TPV and TRT for 40° saccadic responses retained significance when only the 10 emmetropic subjects with similar axial lengths (ranged from 23.00–24.19 mm), but with different OR values (ranged from 0.0153–0.018 mm Hg/ μ L), were examined. Ocular rigidity was positively correlated with PV for both abduction ($R^2 = 0.43$, $F = 6.01$, $P = 0.039$, $y = 17161x + 299.92$) and adduction ($R^2 = 0.48$, $F = 7.36$, $P = 0.027$, $y = 12212x + 373.71$). Ocular rigidity was negatively correlated with TPV for both abduction ($R^2 = 0.49$, $F = 7.92$, $P = 0.023$, $y = -1201.4x + 63.054$) and adduction ($R^2 = 0.49$, $F = 7.97$, $P = 0.022$, $y = -1569.9x + 70.576$). Similarly, OR was negatively correlated with TRT for both abduction ($R^2 = 0.55$, $F = 9.76$, $P = 0.014$, $y = -3874.7x + 220.16$) and adduction ($R^2 = 0.50$, $F = 7.98$, $P = 0.022$, $y = -16936x + 446.99$).

DISCUSSION

Our study and that of Müller et al.²⁶ show that dynamic characteristics of saccadic eye movements are affected by OR. In addition, the findings of this study show that subjects with high OR generate saccadic eye movements with significantly faster PV and significantly shorter TPV than either the medium or low OR groups. We also find that the group with low OR had lower PV than the medium OR group confirming the findings of a previous study,²⁴ and we have now extended this finding to subjects with high OR (hyperopes).

While Hartwig et al.²⁵ reported that myopes and emmetropes have similar saccadic eye movement characteristics, our findings show that myopes with larger axial length and lower OR have significantly slower saccades compared with both emmetropes and hyperopes with higher values of OR. Hartwig

et al.²⁵ measured 10° and 20° saccades only, whereas in the present study we have measured saccades up to 40° in both horizontal directions. Our data show that the difference in saccadic characteristics becomes more noticeable for larger saccades (i.e., 30° and 40°). Additionally, Hartwig et al.²⁵ used predictable stimuli that might alter the saccadic response characteristics. By comparison, predictability is minimized in our study by randomization of stimulus presentation and by rejecting any response with latency shorter than 90 ms as a possible anticipatory response.^{31,32,35} Also, only a few of the myopic subjects in the study of Hartwig et al.²⁵ had MSE less than or equal to -4.00 D and our data (Fig. 4) show that the OR of myopic subjects with MSE up to -3.00 D shows considerable overlap with OR in emmetropic subjects. As Hartwig et al.²⁵ did not measure OR, we cannot determine whether there was a difference in OR between their subject groups. The findings of the current study suggest that the range of refractive error examined by Hartwig et al.²⁵ means that the OR values in the myopic subjects could be similar to those in the emmetropic subjects and this could be the reason why they fail to find any difference in the characteristics of saccadic eye movements between the two groups. In addition, as we show in the current study, the effect of OR upon the saccadic eye movement characteristics increases with the increasing size of the saccade; hence, it is also possible that the smaller magnitude of saccadic eye movements measured by Hartwig et al.²⁵ could be the reason why they do not find any differences in saccadic characteristics between myopic and emmetropic subjects.

Axial length showed the expected negative linear relationship with OR in agreement with previous studies.^{16–20} The longer axial length eyes in the present study have a significantly lower rigidity compared with shorter axial length eyes (Fig. 4). Previous work shows that an increase in axial length is associated with a decrease in scleral thickness^{19,21,22} due primarily to a reduction in the scleral collagen contents resulting from thinning of collagen fiber bundles and a reduction in the size of the individual collagen fibrils.^{19,22} Clearly, this thinning of the sclera has a significant effect upon the OR of the eye. Relatively few studies have measured OR in shorter (hyperopic) eyes^{16,17,20} although Dastiridou et al.²⁰ reported recently a linear relationship between OR and axial length in hyperopic subjects, with OR increasing as axial

length decreased. They showed that this relationship was a continuation of the previously reported relationship between OR and axial length in larger (myopic) eyes. Our findings support those of Dastiridou et al.²⁰ as we also find a linear relationship between OR and axial length extending continuously from myopia to hyperopia.

Robinson²³ demonstrated that ocular mass is negligible in determining the time course of saccadic eye movements. He showed that the force generated by the extraocular muscles was found to be sufficient to overcome an applied weight of 18 g,²³ which is substantially greater than the typical weight of the eye. Thus, it is unlikely that differences in ocular mass between the subjects would explain the differences in eye movement dynamics identified in the current study or that by Müller et al.²⁴

Ocular rigidity is a property of the eye, which could affect the way that the force generated by the extraocular muscles is transferred to the globe. It is possible that in subjects with high OR, and therefore “stiffer” eyes the transfer of force may be more efficient leading to a shorter TPV and a higher PV. The opposite would be true in subjects with low OR. The fact that OR shows a significant relationship with all the saccadic parameters, even in a subgroup of subjects with similar axial lengths suggests that the difference in saccadic characteristics is not related to the mass or inertia of the eye but to the tissue characteristics quantified by OR. A previous study has shown that the thinning of scleral tissue found in larger eyes may be less efficient at transferring the force of the extraocular muscles.³⁶ There is no literature reporting eye movement characteristics in subjects with high OR (and shorter eyes) and our findings show the previously described effect of low OR upon saccadic eye movement dynamics^{24,36} can be extended to subjects with high OR (and shorter axial lengths) who are generally hyperopic.

Saccadic eye movement parameters, including PV, TPV, and TRT showed significant response asymmetry between abductive and adductive movement in the present study with the temporal saccades being faster than the nasal saccades in all subject groups. Furthermore, these asymmetries did not differ significantly between the three subject groups. Asymmetries between abduction and adduction have been reported in previous studies,^{3,37-39} and have been attributed to the fact that the medial rectus muscle is thicker⁴⁰ and stiffer than the lateral rectus muscle.^{41,42} Additionally, the resistance force exerted by the vertical and the oblique recti during horizontal movement is greater for adductive movements⁴³ and the tissue stiffness restraining movement of the globe in the nasal direction is 11% greater than in the temporal direction.⁴² It has also been shown that arrival of premotor signals at medial rectus motoneurons is delayed compared with that for lateral rectus motoneurons, which may lead to a difference in timing for the activation of the medial and lateral rectus muscles causing asymmetrical saccades.⁴⁴ The data of the present study cannot differentiate between possible causes of asymmetrical saccades; however, it is interesting that our data shows that these saccadic asymmetries are the same in each OR group suggesting that the characteristics of the extraocular muscles do not differ between the groups.

Response latency was the same in all groups irrespective of the size or direction of the stimulus. This suggests that the differences in saccadic eye movement dynamics found in the present study are unrelated to the sensory encoding of the saccadic response, but are more likely to be found in the characteristics of the physical plant, comprising the extraocular muscles and ocular globe. Response latency in this study was longer than that found in other studies,^{5,8,9,31} mainly because the subjects in the current study were naive and had no training prior to participating in the experiment. Also

randomization^{32,45} of stimulus presentation would minimize any learning effect, thus reducing anticipation of stimulus movement.

CONCLUSIONS

The known relationship of OR with myopia can be extended to shorter hyperopic eyes, which are found to have higher OR. The dynamic characteristics of saccadic eye movements are found to vary systematically with OR. These findings suggest that the structural characteristics of the eye are an important factor in determining dynamic characteristics of eye movements.

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