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Rectus Extraocular Muscle Size and Pulley Location in Concomitant and Pattern Exotropia

Rui Hao, MD,[1,2] Soh Youn Suh, MD,[1] Alan Le, BS,[3] Joseph L. Demer, MD, PhD[1,3,4,5,6]

Purpose: To determine whether rectus extraocular muscle (EOM) sizes and pulley locations contribute to exotropia, we used magnetic resonance imaging (MRI) to measure these factors in normal control participants and in patients with concomitant and pattern exotropia.

Design: Prospective case-control study.

Participants: Nine patients with concomitant exotropia, 6 patients with pattern exotropia, and 21 orthotropic normal control participants.

Methods: High-resolution surface-coil MRI scans were obtained in contiguous, quasicoronal planes. Rectus pulley locations were determined in oculocentric coordinates for central gaze, supraduction, and infraduction. Cross sections in 4 contiguous image planes were summed and multiplied by the 2-mm slice thickness to obtain horizontal rectus posterior partial volumes (PPVs).

Main Outcome Measures: Rectus pulley locations and horizontal rectus PPVs.

Results: Rectus pulleys were located differently in patients with A-pattern, versus V- and Y-pattern, exotropia. The lateral rectus (LR) pulleys were displaced significantly superiorly, the medial rectus (MR) pulleys were displaced inferiorly, and the inferior rectus pulleys were displaced laterally in A-pattern exotropia. However, the array of all rectus pulleys was excyclorotated in V- and Y-pattern exotropia. The PPV of the medial rectus muscle was statistically subnormal by approximately 29% in concomitant, but not pattern, exotropia ($P < 0.05$). The ratio of the PPV of the LR relative to the MR muscles in concomitant exotropia was significantly greater than in control participants and those with pattern exotropia ($P < 0.05$).

Conclusions: Abnormalities of EOMs and pulleys contribute differently in pattern versus concomitant exotropia. Abnormal rectus pulley locations derange EOM pulling directions that contribute to pattern exotropia, but in concomitant exotropia, pulley locations are normal, and relatively small medial rectus size reduces relative adducting force. *Ophthalmology 2016;■:1–9 © 2016 by the American Academy of Ophthalmology.*

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At their points of transit through posterior Tenon's fascia, the rectus extraocular muscles (EOMs) are encircled by connective tissue sleeves composed of elastin, collagen, and, in some cases, smooth muscle.[1,2] It is evident from high-resolution magnetic resonance imaging (MRI) scans obtained using surface coils that these tissue sleeves act as pulleys, greatly limiting sideslip over the globe of the posterior EOM paths during duction, and in the process influencing EOM pulling direction.[3–5] However, even using high-resolution MRI, the low intrinsic contrast of connective tissues usually precludes visualization of pulleys with detail sufficient to resolve the precise locations of the rectus pulleys. This seeming conundrum is actually not a major limitation because the EOMs themselves are readily imaged by MRI and always pass through the pulleys; it is only necessary to determine the precise paths of the EOMs to identify the possible locations of their encircling pulleys. In eccentric gazes, the pulleys prevent shift of the straight posterior paths of the EOMs and, in so doing, abruptly inflect their paths so that, more anteriorly, the tendons follow different straight paths angulated to correspond to half the amount of globe rotation. The anatomic point of sharp inflection between the stable posterior EOM path versus the moving anterior path defines each pulley location functionally.[6] Conceptually, EOMs direct their forces toward the pulleys as if pulleys were their mechanical origins, so the locations of the inflections in EOM paths define their pulling directions and thus their oculorotary actions.[7] Although precise determination of the 3-dimensional locations of the rectus pulleys requires that imaging be performed in multiple gaze positions, including secondary or tertiary ones, studies of pulley locations to date have made the task easier: the anteroposterior positions of rectus pulleys remain normal even if their horizontal and vertical positions are grossly abnormal. This fortunate circumstance implies that pulley coordinates in the coronal plane may be approximated accurately by the horizontal and vertical rectus EOM positions determined from quasicoronal

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MRI planes located between the posterior pole and equator when obtained in central gaze.

Strabismus is described as concomitant when its angle is independent of gaze direction, yet in approximately 25% of cases, incomitant pattern deviations occur in which the angle changes with gaze direction.[8] Heterotopic (displaced) pulleys have been proposed to be among the causes of incomitant strabismus,[9,10] including congenital A-patterns with less esotropia in infraversion and V-patterns with greater exotropia or less esotropia in supraversion. Pulley heterotopy can misdirect EOM force to produce overelevation or underelevation in adduction that may simulate oblique EOM overcontraction or undercontraction.[9,10] Small mislocations (<2 mm) of rectus EOM pulleys can cause incomitant strabismus. Clark et al[9] noted that abnormal superior displacement of a lateral rectus (LR) pulley can generate the clinical pattern often termed *superior oblique (SO) muscle overaction*, which causes A-pattern strabismus, and an inferiorly displaced LR pulley can generate V-pattern strabismus. Previous studies of EOM pulley positions in pattern strabismus measured these positions relative to the bony orbit,[4,9,11] but the effect could be confounded by translation of the eye itself within the orbit. Beyond static mislocations of pulleys, resultant patterns of strabismus may depend on static pulley positions, pulley instability, and coexisting globe translation that alter pulley locations relative to the globe.[12]

Modest pulley displacement also may result from abnormal ocular torsion,[13] and modest changes in pulley positions are induced by aggressive surgical EOM transpositions performed for macular transposition.[14] Recently, combined mechanical effects of medial rectus (MR), superior rectus (SR), and inferior rectus (IR) muscle pulley displacements alone were found to explain the pattern of incomitant strabismus in SO palsy, although such pulley displacements were small.[15]

Consensus is scarce regarding causes of concomitant strabismus. Electrophysiologic recordings of the horizontal rectus motor neurons in monkeys with experimental strabismus found the relationships between motor neuron firing rate and eye position to be the same in strabismic and normal monkeys.[16,17] Magnetic resonance imaging examinations in humans with concomitant esotropia show that the MR muscle is larger than normal, but LR muscle size is not subnormal. This suggests that human concomitant esotropia is associated with peripheral EOM abnormality,[18] yet it remains mysterious how abnormally sized EOMs could be commanded by normal motor unit behavior to execute normal eye movements, and uncertainty surrounds whether abnormal EOM size is the cause or effect of strabismus. Changes in EOM length do not explain strabismus. Rabinowitz and Demer[19] found normal horizontal rectus EOM path lengths in intermittent and alternating esotropia and exotropia.

Although pulley heterotopy and instability have been observed in pattern strabismus,[9,10] it is unknown whether abnormal pulley locations contribute to concomitant exotropia. It remains possible that the horizontal EOMs also may become larger or stronger in pattern exotropia. This study sought to obtain MRI data on rectus pulley positions, as well as horizontal muscle size, to determine whether abnormalities are associated with concomitant or pattern exotropia.

Methods

After obtaining written informed consent according to a protocol conforming to the Declaration of Helsinki and approved by the institutional review board of the University of California, Los Angeles, we prospectively studied 9 patients with constant, concomitant exotropia who had a mean age ± standard deviation of 34±13 years and 6 patients with pattern exotropia with a mean age ± standard deviation of 29±10 years, including 2 patients with A-pattern exotropia, 2 with V-pattern exotropia, and 2 with Y-pattern exotropia. These included all patients recruited for a prospective study of MRI in strabismus between July 2002 and January 2013 who had nonparalytic exotropia but had not undergone prior strabismus surgery, who underwent orbital MRI examination in quasicoronal planes in central gaze, and who had adequate image quality for analysis. We compared these with 21 normal control participants with a mean age ± standard deviation of 31±14 years who were orthotropic and had vision correctable to normal with spectacles if necessary. No strabismic patient had been included in prior studies of pulley positions.

Control participants were examined to verify normal ocular motility, stereopsis, and binocular alignment. All cases of exotropia were constant rather than intermittent. Exotropic patients had similar visual acuity bilaterally. By prism and cover testing, patients with A-pattern disease exhibited exotropia at least 10 prism diopters more in infraversion than supraversion. Patients with V-pattern exotropia had exotropia of at least 15 prism diopters more in supraversion than infraversion. Y-pattern exotropia was diagnosed when exotropia was greatest in supraversion but similar in central gaze and infraversion.

Participants underwent high-resolution T1- or T2-weighted MRI with a 1.5-Tesla scanner (Signa; General Electric, Milwaukee, WI) and surface coils (Medical Advances, Milwaukee, WI), as detailed elsewhere,[3,20] including monocular fixation of a centered afocal target by the eye scanned to eliminate eye position as a potential confounder.[9,21,22] Axial images were obtained to localize placement of subsequent higher-resolution quasicoronal images perpendicular to the orbital axis. Digital MRI images were quantified with the computer program ImageJ64 (National Institutes of Health, Bethesda, Maryland; available at: http://imagej.nih.gov/ij/). Horizontal rectus EOMs were outlined manually in coronal plane images.[23,24] Rectus EOM locations were determined by their area centroids,[6] which were transformed into a standard coordinate system originating at the center of the spherical globe[6] as determined in 3 dimensions from multiple cross-sectional images.[4,25] Data were rotated about the globe center using cranial landmarks into a standard anatomic coordinate system whose positive coordinates were anterior, superior, and lateral.[6] In most cases, imaging was performed in central gaze, supraduction, and infraduction, enabling determination of the anteroposterior locations of the horizontal rectus pulleys from the inflections in EOM paths in the eccentric gazes. Although imaging also was performed in horizontal eccentric gazes, it was not always possible to image the paths of the vertical rectus EOMs sufficiently anteriorly without injected contrast to identify path inflections that would have defined the anteroposterior locations of the pulleys. Therefore, published anteroposterior pulley coordinates were assumed to determine anteroposterior coordinates of the vertical rectus pulleys.

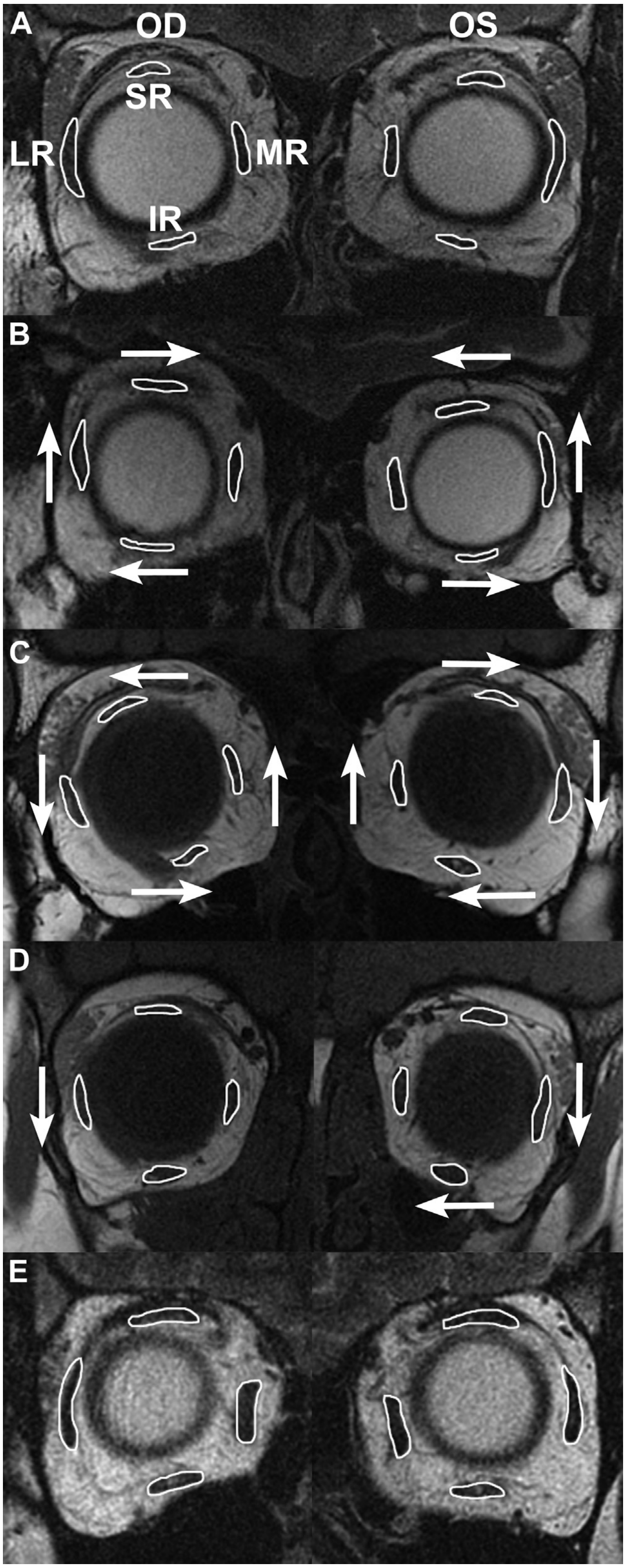

Figure 1. Magnetic resonance imaging scans from representative subject groups: (A) normal (T2-weighted image); (B) A-pattern exotropia, in which lateral rectus (LR) muscles are displaced superiorly, inferior rectus (IR) muscles are displaced laterally, and superior rectus (SR) muscles are displaced medially (T2-weighted image); (C) V-pattern exotropia, in which array of all rectus muscles is excyclorotated bilaterally (T1-weighted image); (D) Y-pattern exotropia, in which LR muscles in both eyes are displaced inferiorly and the IR muscle in the left eye is displaced nasally (T1-weighted image); and (E) concomitant exotropia (T2-weighted image). Arrows indicate directions of significant muscle displacements. MR = medial rectus muscle; OD = right eye; OS = left eye.

The quasicoronal image plane closest to the junction of the globe and optic nerve was defined to be image plane 0, with more anterior image planes designated positive and posterior planes designated negative. Cross sections in image planes −4, −5, −6, and −7 (8−14 mm posterior to the globe−optic nerve junction) were summed and multiplied by 2 mm to form posterior partial volumes (PPVs).[26] Results were analyzed using analysis of variance (GraphPad Prism version 6; GraphPad Software, La Jolla, CA). Differences were considered significant at $P < 0.05$.

Results

Rectus Pulley Locations in the Coronal Plane

Cross sections of rectus EOM pulleys were readily identifiable in quasicoronal MRI scans. Figure 1A illustrates a binocular MRI scan at the level of the rectus EOM pulleys in a representative control participant. It is evident that rectus cross sections are bilaterally symmetrical, with similar vertical positions of all 4 horizontal rectus EOMs and with the SR muscle located slightly lateral to the IR muscle. This arrangement also was typical of concomitant exotropia (Fig 1E). A quantitative analysis is illustrated in Figure 2, which superimposes mean coordinates of the 4 rectus pulleys both in control participants and in patients with concomitant exotropia. The pulley locations of normal control participants are consistent with those reported in a previous study[6] and were statistically indistinguishable from those of patients with concomitant exotropia ($P > 0.05$).

Unlike patients with concomitant strabismus, all 6 patients who had exotropia exhibiting V-, Y-, or A-pattern incomitance had at least 1 heterotopic rectus pulley significantly outside the 95% confidence interval of normal. Figure 1B−D demonstrates MRI examples of the consistent finding of abnormal rectus pulley locations in pattern exotropia. In A-pattern exotropia, the array of rectus pulleys appears bilaterally incyclorotated (Fig 1B), with the LR pulley superior to the MR pulley and the SR pulley nasal to the IR pulley. The opposite finding was typical of V-pattern exotropia (Fig 1C), where the array of rectus pulleys appears bilaterally excyclorotated, with the LR pulley inferior to the MR pulley and the SR pulley markedly temporal to the IR pulley. The foregoing effect was less extreme in Y-pattern exotropia (Fig 1D). Quantitative analyses of pulley positions are illustrated in Figure 3, with examples of 2 patients each with A-, V-, and Y-pattern exotropia.

Anteroposterior Pulley Locations

To determine anteroposterior pulley locations, MRI examination was repeated in multiple vertical gaze positions only in patients with pattern exotropia. Figure 4 shows lateral projections of the vertical components of the anteroposterior paths of the LR and MR muscles for A-pattern exotropia in central gaze, supraduction, and infraduction. There was roughly 3 mm of superior displacement from normal of the posterior LR path and roughly 2.5 mm of inferior shift of the posterior MR path; these posterior paths were similar in all vertical gaze positions. However, approximately 10 mm posterior to the globe center,

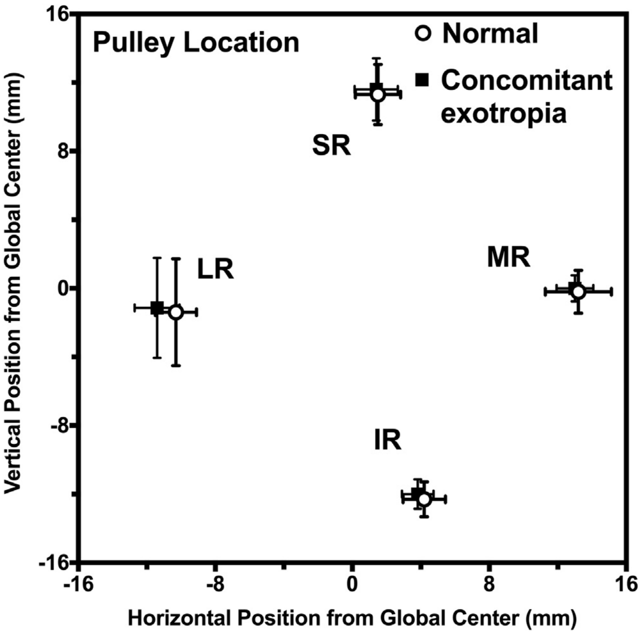

Figure 2. Graph showing the rectus pulley locations of control participants and patients with concomitant exotropia. No pulley positions are abnormal in concomitant exotropia. Error bands, ±2 standard deviation. IR = inferior rectus muscle; LR = lateral rectus muscle; MR = medial rectus muscle; SR = superior rectus muscle.

the LR path was inflected sharply inferiorly in infraduction and superiorly in supraduction as the anterior LR tendon traveled anteriorly from its pulley to the correspondingly rotated scleral insertion (Fig 4A). The anteroposterior location of this inflection point in the LR muscle path was similar for both infraduction and supraduction and corresponds to the normal anteroposterior range of pulley locations denoted by the rectangle in Figure 4. Although anteroposterior location of the LR pulley for the case of A-pattern exotropia in Figure 4 thus may seem to be normal, inflections of LR muscle path during vertical gaze shift were 2 to 4 mm superior to the vertical extent of the normal pulley location denoted by the gray rectangle in Figure 4. Medial rectus muscle paths for the same case of A-pattern exotropia are illustrated in the right panel of Figure 4. Inverse to the vertical path of the LR pulley, the posterior MR path may be seen to be shifted approximately 3 mm inferiorly in all vertical gaze positions, but the path exhibits vertical inflection 5 to 6 mm posterior to the globe center within the posterior end of the normal range, denoted by the gray rectangle (Fig 4B). This implies that the MR pulley is displaced significantly inferiorly but remains in a normal anteroposterior location.

Figure 5 shows lateral projections of the vertical components of the anteroposterior paths of the LR and MR muscle paths in V-pattern exotropia in central gaze, supraduction, and infraduction. There was roughly 2.5 mm of inferior displacement from normal of the posterior LR muscle path and roughly 2 mm superior shift of the posterior MR muscle path; these posterior paths were similar in all vertical gaze positions. However, approximately 10 mm posterior to the globe center, the LR muscle path was inflected sharply inferiorly in infraduction and superiorly in supraduction as the anterior LR tendon traveled anteriorly from its pulley to the correspondingly rotated scleral insertion (Fig 5A). The anteroposterior location of this inflection point in the LR muscle path was similar for both infraduction and supraduction and corresponds to the normal anteroposterior range of pulley locations denoted by the rectangle in Figure 5. Although anteroposterior location of the LR pulley for the case of V-pattern exotropia in Figure 5 thus may be seen to be normal, inflections of the LR muscle path during vertical gaze shift were 1 to 3 mm inferior to the vertical extent of the normal pulley location denoted by the gray rectangle in Figure 5. Medial rectus muscle paths for the same case of V-pattern exotropia are illustrated in the right panel of Figure 5. Inverse to the vertical path of the LR muscle, the posterior MR muscle path may be seen to be shifted approximately 2 mm superiorly in all vertical gaze positions, but it exhibits vertical inflection approximately 5 mm posterior to the globe center at the posterior limit of the normal range, denoted by the gray rectangle (Fig 5B). This implies that the MR pulley is displaced significantly superiorly but remains in a normal anteroposterior location in this patient.

Computational Simulation

Computational simulations of binocular alignment were performed using measured rectus coronal plane pulley locations in patients with A-, V-, and Y-pattern exotropia using the Orbit 1.8 model (Eidactics, Inc., San Francisco, CA) (see Supplemental Fig S1, available at www.aaojournal.org). Implementing only these abnormalities that were measured in the same oculocentric coordinates used by Orbit 1.8, the computer simulations replicated the 3 patterns of incomitance observed for these patients in infraversion and supraversion. These simulations suggest that the pulley heterotopies may cause the incomitant exotropia.

Horizontal Rectus Extraocular Muscle Volumes

We measured cross-sectional area distributions in each image plane of the horizontal rectus EOMs in central gaze and plotted these against the anteroposterior position in the orbit (Fig 6) to determine whether EOM size varies with type of exotropia. There were no significant differences for LR and MR muscles in control participants and in patients with concomitant and pattern exotropia. However, Figure 6 demonstrates greater difference between LR and MR muscles in patients with concomitant exotropia. From the summed cross sections, we computed the PPVs of the LR and MR muscles (Fig 7). In concomitant exotropia, the PPV of the MR muscle was 28.6% smaller than normal ($P = 0.01$). The ratio of PPV of the LR muscle to the MR muscle was 1.01±0.15 for control participants and 0.86±0.16 for patients with pattern exotropia (Fig 8; $P = 0.05$), but it was significantly greater than both at 1.47±0.37 in concomitant exotropia ($P = 0.006$).

Superior Oblique Posterior Partial Volume

Mean PPV of the SO was 116±7 mm^3 in control participants, 117±5 mm^3 in concomitant exotropia, 123±4 mm^3 in A-pattern exotropia, and 112±3 mm^3 in V- and Y-pattern exotropia, not varying significantly among groups. Although PPV of the SO did not differ significantly from normal in any of the exotropia groups, it was approximately 9% smaller in V- and Y-pattern exotropia than in A-pattern exotropia ($P = 0.03$). Inferior oblique muscle size could not be measured from the image planes acquired.

Discussion

Pulleys in Concomitant and Pattern Exotropia

High-resolution MRI demonstrated that rectus EOM pulleys are located normally in concomitant exotropia, thus

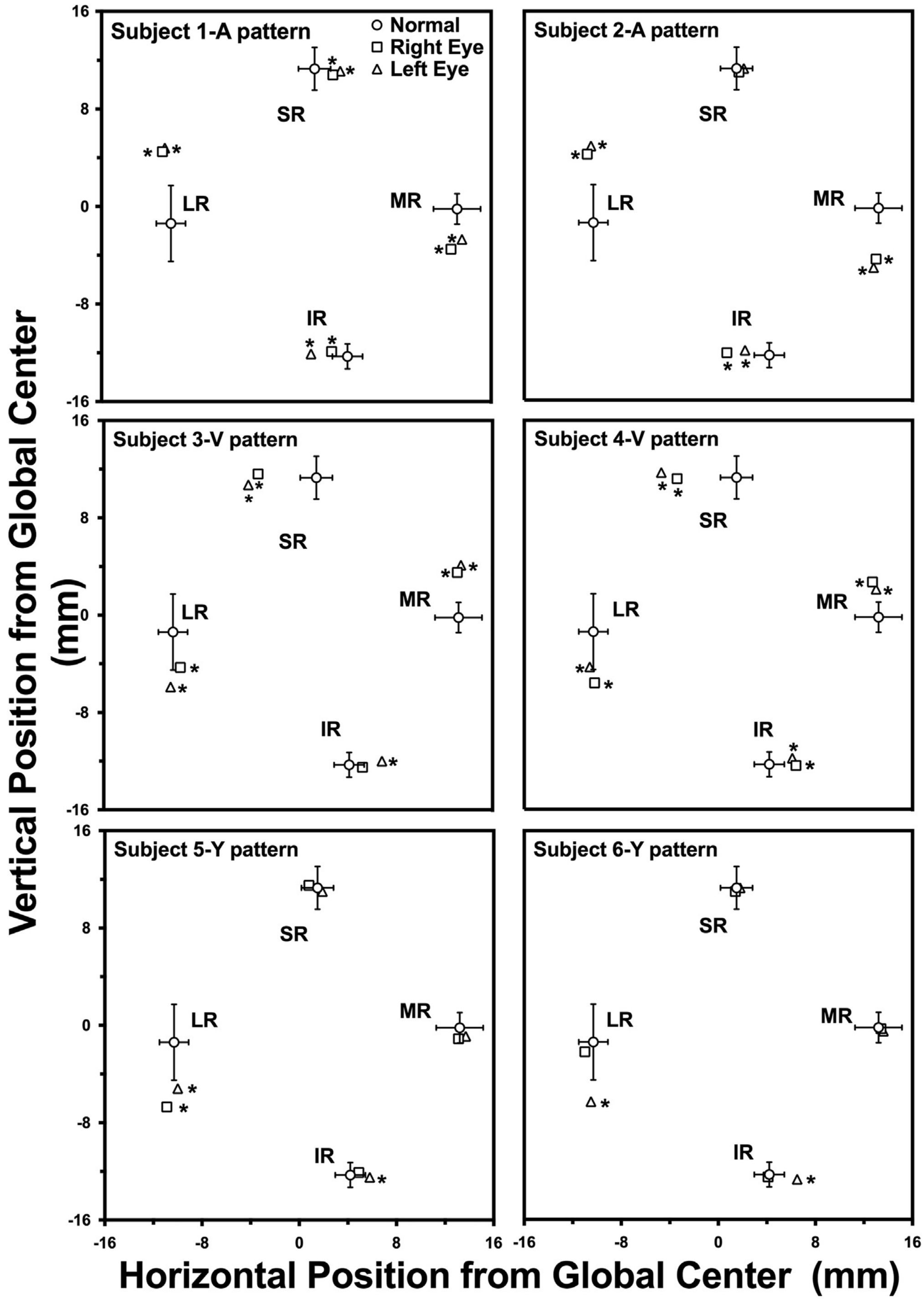

Figure 3. The locations of rectus extraocular muscle pulleys in control participants and patients with pattern exotropia, relative to the orbital center. Left orbits have been reflected to the configuration of right orbits. Error bands ±2 standard deviations. *Significantly abnormal. IR = inferior rectus; LR = lateral rectus; MR = medial rectus; SR = superior rectus.

excluding coronal plane pulley heterotopy as a causal or associated factor in this form of strabismus. In contrast, all 6 patients who had exotropia with V-, Y-, or A-pattern incomitance exhibited at least 1 heterotopic rectus pulley significantly outside the 95% confidence region for normal oculocentric coordinates in the coronal plane. This finding confirms and extends the observations of a previous study that examined the normal rectus pulley positions relative to the orbit (orbitocentric coordinates).[6] The current findings support the conclusion that displacement of rectus pulleys perpendicular to their planes of action by only a few millimeters may increase the risk of

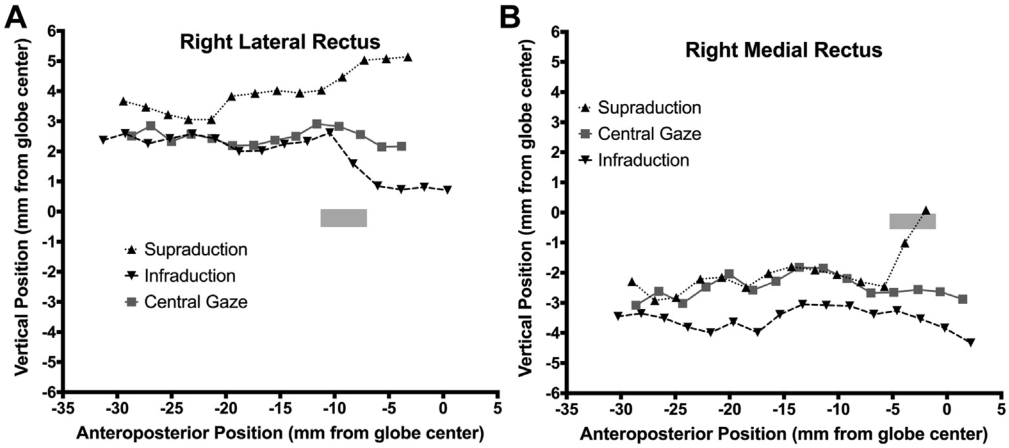

Figure 4. The vertical area centroid positions of the (**A**) right lateral rectus (LR) and (**B**) right medial rectus (MR) muscles in a subject with A-pattern exotropia, plotted along the anteroposterior orbital axis, and referenced to the globe center. The muscle paths in central gaze indicate marked superior displacement of the LR and inferior displacement of the MR pulleys, well outside the 95% confidence regions for normal pulleys[6] (gray rectangles).

strabismus by altering EOM pulling directions sufficiently to exceed compensatory capabilities of fusional vergence.[27]

For both patients with A-pattern exotropia, the LR pulley was shifted superiorly and the IR pulley was shifted laterally. In patients with V-pattern exotropia, the LR pulley was displaced inferiorly, the IR pulley was displaced medially, the MR pulley was displaced superiorly, and the SR pulley was displaced laterally in both eyes (Fig 2C), amounting to bilateral excyclorotation of the entire rectus pulley array. This phenomenon was incomplete in patient 4, who exhibited abnormal positions of only the left MR and right IR pulleys. The patient with Y-pattern exotropia showed pulley locations similar to those in V-pattern exotropia, with the LR bilaterally shifted inferiorly and the left IR pulley shifted nasally.

Previous studies demonstrated the effects of insertional transposition[11,20] and showed that conventional recession and resection of horizontal rectus EOMs did not result in horizontal or vertical displacement of their pulleys.[28] Sekeroglu et al[29] found that half-tendon width transposition of horizontal muscles significantly decreased the amount of V pattern. Children with craniosynostosis often have V-pattern horizontal strabismus.[30,31] One explanation for pattern strabismus in craniosynostosis is excyclotorsion of the orbital contents, resulting in oblique pulling directions for the nominally rectus EOMs.[31–33] Weiss et al[34] provided evidence that the pattern and dissociated vertical strabismus associated with Crouzon syndrome can be caused by extorsion of the rectus pulley array. The present cases illustrate that abnormalities of locations of horizontal rectus pulleys occur in pattern exotropia, consistent with a prior report of 2 patients.[4] There are several reasons why the present findings suggest rectus pulley heterotopy to be the probable cause, rather than the effect, of pattern strabismus. First, SO palsy, a well-recognized cause of

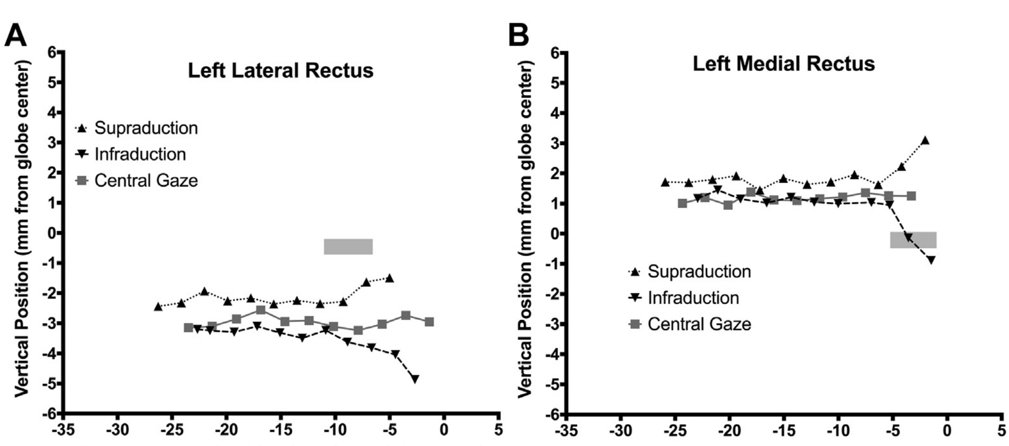

Figure 5. Vertical area centroid positions of the (**A**) left lateral rectus (LR) and (**B**) left medial rectus (MR) muscles in V-pattern exotropia plotted along the anteroposterior orbital axis, referenced to the globe center. Muscle paths in central gaze reflected marked inferior displacement of the LR and superior dispacement of the MR pulleys, well outside the 95% confidence region for normal pulleys[6] (gray rectangles).

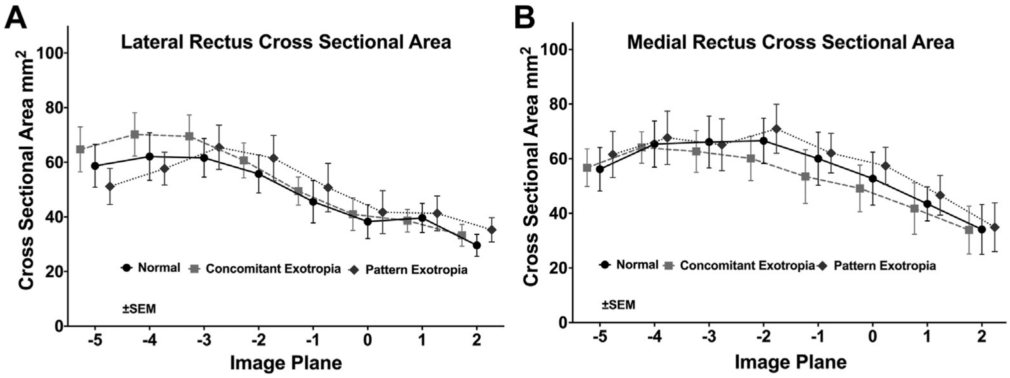

Figure 6. The mean cross-area (in square millimeters) of the (**A**) lateral rectus and (**B**) medial rectus muscles in 2-mm-thick quasicoronal planes from posterior at left to anterior at right for control participants and patients with concomitant and pattern exotropia. Differences were not significant ($P = 0.67$ for LR muscle and $P = 0.43$ for MR muscle, analysis of variance). SEM = standard error of the mean.

paralytic pattern strabismus, produces small pulley displacements of MR, SR, and IR muscles, but not of the LR muscle, suggesting that these pulley displacements are not secondary to excyclotorsion caused by SO palsy.[15] Second, even a 16-mm inferior oblique muscle advancement performed in 1 patient that corrected 25° incyclotropia induced by macular translocation did not shift the MR pulleys as much as observed here in V- and Y-pattern exotropia.[15] Third, computational simulation using the Orbit 1.8 model predicted the alignment effects of the pulley heterotopies in all cases of pattern exotropia. Abnormal rectus pulley locations may explain why some cases of pattern strabismus respond poorly to oblique EOM surgery. This suggests that orbital imaging may be valuable clinically in surgical planning for patients with pattern exotropia.

Multipositional MRI sufficient to locate anteroposterior pulley locations by EOM path inflections was performed only in some patients with pattern exotropia. Anteroposterior locations of the LR and MR pulleys were normal in the cases of A- and V-pattern exotropia that were examined, supporting the conventional assumption that anteroposterior pulley position remains normal even in the setting of considerable rectus pulley heterotopy in the coronal plane. Therefore, anteroposterior pulley location was presumed to be normal for the other cases of exotropia.

Posterior Partial Volumes of Extraocular Muscles

Patients with concomitant exotropia had significantly subnormal PPV for the MR muscle and a trend toward supranormal PPV of the LR muscle, such that the ratio of LR−MR muscle PPV significantly exceeded normal. It seems logical to presume that larger EOMs would be

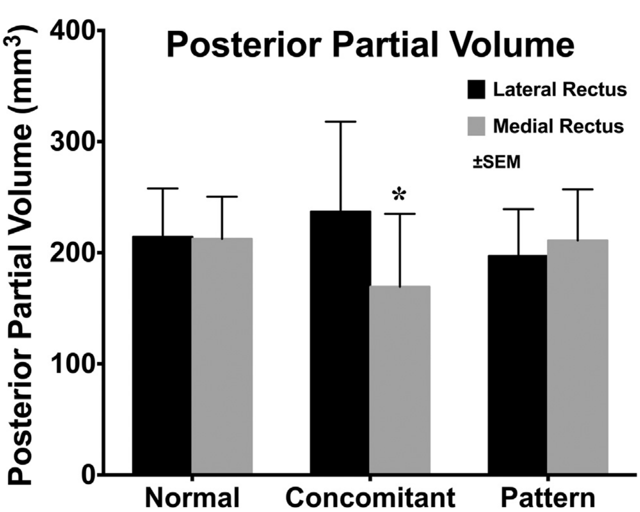

Figure 7. The posterior partial volumes of the lateral rectus and medial rectus muscles in control participants and patients with concomitant and pattern exotropia. *Statistically subnormal ($P < 0.05$). SEM = standard error of the mean.

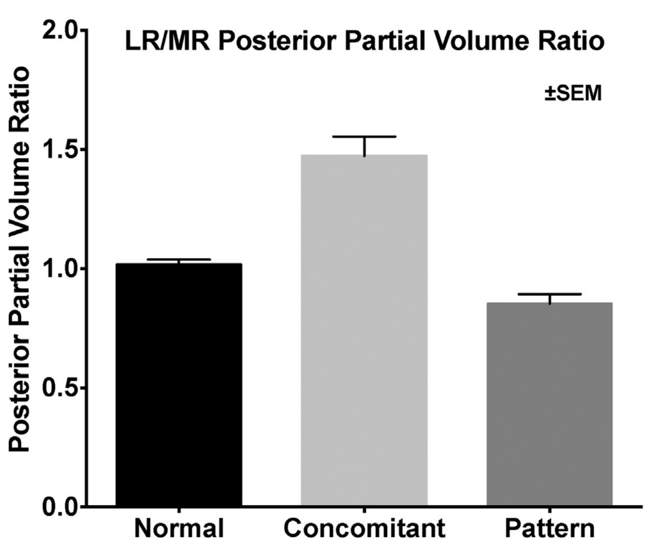

Figure 8. The ratio of lateral rectus (LR) to medial rectus (MR) muscle posterior partial volume in control participants and patients with concomitant and pattern exotropia. The ratio was significantly greater in the concomitant exotropia group than in the other groups ($P < 0.05$). SEM = standard error of the mean.

stronger than smaller ones because changes in EOM size closely correlate with contractility.[24] In the context of the normal rectus pulley locations observed here in concomitant exotropia, larger LR than MR muscle PPV seems to offer a satisfactory mechanism for understanding the exotropia on the basis of abducting LR muscle strength exceeding adducting MR muscle strength. Differential strength in the LR−MR antagonist muscle pair may be related to the tendency for recurrence of exotropia after surgical treatment. It may be that the MR muscle in concomitant exotropia is weaker than in control participants and patients with pattern exotropia, in whom the pattern of the strabismus presumably is the result of normal EOM force exerted in abnormal directions due to heterotopic pulleys.

The volume of the SO muscle is reflective of its strength and did not differ significantly from normal in concomitant or any form of pattern exotropia. Although PPV of the SO muscle in V- and Y-pattern exotropia was approximately 9% less than in A-pattern exotropia, the significance of this small difference is uncertain. For comparison, the ratio of LR−MR muscle PPV in concomitant exotropia was approximately 47% greater than normal (Fig 8). A larger sample of patients would be required to determine whether the SO muscle plays a significant role in the pathophysiology of pattern exotropia. This investigation did not examine the inferior oblique muscle for a possible relationship to exotropia. Although highly significant in all groups with pattern exotropia, pulley heterotopy by itself would not in any obvious way determine whether associated strabismus would be esotropia versus exotropia; other factors, such as central innervational commands, must be presumed decisive in this regard.

In summary, this study confirms and extends previous reports of pulley positions in pattern exotropia[4,5,7,9] and suggests that PPV changes in horizontal rectus EOMs may be related to concomitant exotropia. This study is preliminary in that it included few patients who had concomitant exotropia and pattern exotropia, did not evaluate the inferior oblique muscle, and determined only anteroposterior pulley locations in some cases of pattern exotropia. However, these data indicate that highly significant and widespread coronal plane pulley positions are probably primary abnormalities in pattern exotropia.

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[1] Department of Ophthalmology, David Geffen Medical School at University of California, Los Angeles, Los Angeles, California.

[2] Tianjin Eye Hospital, Tianjin Key Lab of Ophthalmology and Visual Science, Tianjin Eye Institute, Clinical College of Ophthalmology Tianjin Medical University, Peoples Republic of China.

[3] Stein Eye Institute, David Geffen Medical School at University of California, Los Angeles, Los Angeles, California.

[4] Department of Neurology, David Geffen Medical School at University of California, Los Angeles, Los Angeles, California.

[5] Neuroscience Interdepartmental Program, David Geffen Medical School at University of California, Los Angeles, Los Angeles, California.

[6] Bioengineering Interdepartmental Program, David Geffen Medical School at University of California, Los Angeles, Los Angeles, California.

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Conception and design: Hao, Demer

Analysis and interpretation: Hao, Suh, Le, Demer

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Abbreviations and Acronyms:
EOM = extraocular muscle; **IR** = inferior rectus; **LR** = lateral rectus; **MR** = medial rectus; **MRI** = magnetic resonance imaging; **PPV** = posterior partial volume; **SO** = superior oblique; **SR** = superior rectus.

Correspondence:
Joseph L. Demer, MD, PhD, Stein Eye Institute, 100 Stein Plaza, UCLA, Los Angeles, CA 90095-7002. E-mail: jld@jsei.ucla.edu.