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MECHANICAL MODEL APPLICATIONS

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ABSTRACT

The physical plant of the oculomotor system, the eye, the attached muscles and tissues, are modelled.(1) The model allows one to address a particular feature of the oculomotor system such as the insertion change of an extraocular muscle, variation in the neurological command signals, change in eye size, or alterations in the passive or developed force characteristics of the muscle, and to design artificial muscles for certain conditions.

I. Some simple insights into surgical effects can be seen diagramatically.

A. Recession of a muscle to a point near the equator makes it unimportant whether the insertion width is maintained or the muscle is allowed to bunch together, inasmuch as the vertical translation of a horizontal muscle upward or downward is now minimized. (FIGURE 1,A).

B. Recession together with vertical transposition of a muscle, intended to alter the length and tension of a horizontal muscle with vertical gaze, is successfully used in AV patterns. Here, it is relatively desirable to bunch the muscle insertion together to enhance these length changes across the entire width of the muscle. (Figure 1,B).

This will also cause some vertical and torsional torque which balance in the primary position but alter with horizontal rotation. For example, a recession and supra placement of the medial rectus for A-pattern esotropia will tend to elevate the eye in adduction, a usually desirable effect since depression in adduction is ordinarily common in A-pattern.

C. With resection or advancement of a muscle, a very wide swing of vertical force will develop from a centralized insertion point; here it is desirable to maintain the width of the muscle insertion so that the effective line of force is correctly shifted downward and upward with vertical gaze. (FIGURE 1,C).

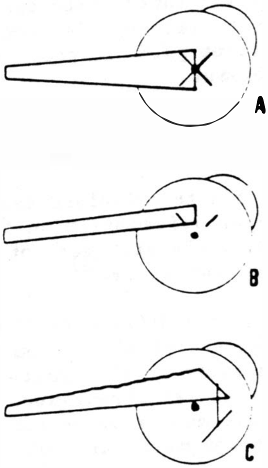


Figure 1. Saggital view of medial rectus. The lines of insertion for 45° vertical gaze positions are shown.

A. Insertion of the MR recessed (moved to transverse axis of rotation of the eye).

B. MR transposed vertically and recessed. The insertion is bunched to a shorter insertion length.

C. Advancement of insertion of MR.

II. Principles from Measuring and Modeling Eye Muscle Forces

A. The average of 29 eyes had 75 grams of developed medial rectus force compared to 59 grams for the lateral, perhaps to balance the normally exotropic position of the eye at rest. It will follow that operations on the medial rectus are slightly more effective than operations with the same number of mm on the lateral rectus.(2)

B. The extraocular muscles and all other tissues normally undergo a ± 10 mm extension and contraction associated with the 50° rotation of the eye from the primary position. At extremes of gaze, the force required to passively rotate the eye or stretch a muscle becomes nonlinear. Operations which exceed about 7 mm on one muscle, 13-14 mm for two muscles, will therefore have nonconcomitant effects beyond about 30° of gaze due to this effect (an additional small effect is also present for medial rectus recessions due to the reduced arc of contact).(3)

C. Recession operations depend on the presence of normal elasticity of the antagonist muscle acting as a spring to take up the slack of the muscle recession. Where the tension from this elasticity is diminished by excessive recession or by palsy, the effect of recession operations will be diminished. The surgeon should not be fooled that release of a tight or contractured muscle will have much effect unless the antagonist is documented to be effectively present.(4) We make it a rule to examine the previously recessed muscle if it is "under-acting" -- often it is further recessed than the records show. Contrariwise, a larger than usual effect can be expected when the antagonist is strong. For example, 25° of vertical correction from 6-7 mm recession of a restricting inferior rectus in endocrine exophthalmos is common because the superior rectus is stronger than normal, increased by isometric contraction against the tight and restricting inferior rectus. Testing of antagonist function is an important guide in proposed recessions in incomitant strabismus.

III. Strabismus Dosage Calculated by Mechanical Measurement

It is possible to calculate the optimum amount of surgical manipulation given information on the developed force of each horizontal muscle, the stiffness of each horizontal muscle, and the stiffness of the globe.(5)

In practice, the difficulty of making these measurements on children, and the practical problem that the noise level of the measurements is substantial, limits their reliability and application in clinical strabismus. For these reasons, partial guides such as the muscle extension manoeuver(6), empirical guidelines as to how much surgical lengthening or tightening should be done(7), operations under local anesthesia where these forces are accurately displayed(8) and adjustable muscle surgery(9) will continue to be important substitutes and alternatives. Clinicians are aware that extraocular muscles following recession operations progressively shorten if left slack. These changes in stiffness of the muscles are probably due to innervational changes which the muscle receives. There is presently no way to model this post-operative behavior with reliability or predictability. Whether the fixing or the nonfixing eye is operated upon to change the length of the muscle (Spielmann) is an example of the variability of innervational input creating these changes.

IV. Active Force Testing in Strabismus.

Isometric muscle force testing readily differentiates between partial paralysis, indicating that recess-resect surgery will be relatively effective, and total paralysis where transposition procedures are to be considered. The simple spring forceps originally conceived by Collins has been improved and made available in Europe by L. Klein, Heidelberg. This is particularly applicable in double elevator palsies wherein the classical indications of muscle function provided by rotation and comitance testing are insufficient. An example of application of these forces and their use in surgical choices is shown in the table for unilateral lateral rectus paralysis. Both modelling and clinical experience confirm that 1) even 10 or 15 grams of residual lateral rectus force can provide large amplitude of eye rotation after recess-resect operations, 2) that an intact or only minimally recessed medial rectus muscle is important as the major horizontal mover, 3) that transposition is required in total palsy (see Russman, this volume), and 4) that recession or Faden operation of the medial rectus of the fellow eye aids comitance and enlarges the field of single binocular vision.

UNILATERAL VI PALSY

Tests			Treatment	
Abduction	Restriction to Abduction	Active Force over 15 gm		
over 15°	no	yes	Recess-resect	Faden/recession MR of fellow eye
no	yes	yes	Recess-resect	"
no	yes	no	Inject MR Transpose SR, IR	"
no	no	no	Transpose SR, IR	"

V. Sideslip of Muscles

Our model normally limits vertical sideslip of horizontal muscles. when high forces are present as in Duane's syndrome, the intermuscular membrane and foot plates no longer restrain horizontal muscles and they may rotate the eye vertically, causing "overshoots" -- this is correctable by recession to reduce muscle force or by Faden or similar techniques to limit sideslip.(10)

A similar side-slip of the vertical rectus muscles in endocrine exophthalmos with restriction is predicted for upgaze. This is seen only occasionally, probably because the large size of the vertical rectus muscles limits their ability to move horizontally in the orbit. A similar prediction in Brown's syndrome with upward gaze is made on the assumption that the point of globe rotation is able to translate from the center of the globe back towards the point of insertion of the restricted superior oblique muscle insertion. Under these conditions, the superior rectus would be expected to slip laterally over the globe in supraduction, and indeed this is found with V-pattern exotropia of the eye in upward gaze. Posterior slip of the inferior oblique (normally restrained by Lockwood's ligament) may cause vertical overaction. Suture of the inferior oblique to the sclera or the inferior rectus at the equator has had variable results, however, because it is not clear when this mechanical cause and when innervational overactivity is the problem.

VI. The brilliant insight of the Faden operation is mentioned for completeness. A full modelling of its effects is indicated elsewhere.(11)

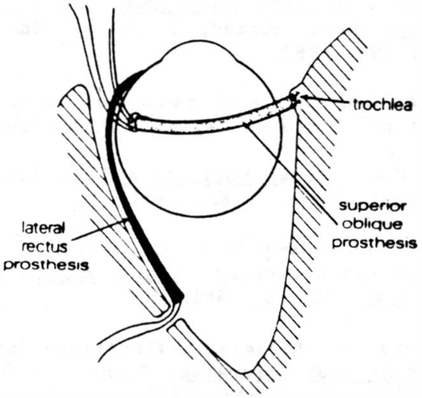
VII. Modelling Inferior Oblique Origin Transposition

Movement of the inferior oblique origin to a point on the lower orbit margin below the visual axis increases the vertical vector of this muscle. Unfortunately, this would leave the muscle too slack to be effective. Tightening the muscle at this point would leave the muscle so short (20 mm) that infraduction would be severely restricted to 20-25°. A further operation could tighten this slack muscle by pulling its insertion upward around the back of the globe, making the inferior oblique a pure vertical rotator in the primary position. Unfortuntely, the relative weakness of the inferior oblique(12) due to its small physical size, limits the added supraduction available from this operation to about 10° and the induced torsion created by this operation would be suprisingly great. Only our full binocular model suffices in telling us that the technical difficulty together with the limited efficacy of this operation makes it of doubtful value for us to pursue.

VIII. Artificial Muscles, Superior Oblique Muscle Prosthesis

The superior oblique extends and shortens only 3–4 mm during 30° of supraduction and 30° of infraduction. Placement of a spring to replace the torsional effect of the paralyzed superior oblique is thus possible. Mechanical modelling tells us that this spring must be of low stiffness, optimally tangent to the length-force curve of the muscle. This observation, together with the 2 to 1 limitation on linear extensibility of silicone rubber springs, means that, ideally, a stiffness of approximately 0.15 grams per degree and a length of approximately 25 mm is required (Collins, to be published). Surprisingly, originating a prosthesis at the trochlea and inserting it at the anterior end of the superior oblique insertion is not optimally effective. A very large change in distribution of superior oblique force into the horizontal and vertical directions is created by small changes in insertion placement near the equator; this indicates a need for post-operative adjustment in tension as well as position anteriorly and posteriorly.

Therefore, we add a harness ring at the end of the prosthesis with sutures leading to posterior and to anterior scleral insertions which can be adjusted the post-operative day.



Lateral Rectus Prosthesis

The stiffness should ideally be about 0.3 grams per degree for a planned range of motion from 15° abduction to 30° adduction, and again requires a long prosthesis of some 30 millimeters. (Collins, to be published). This can be achieved by insertion of the silicone strip near the limbus (gaining 4 or 5 mm), and by creating an origin at a window through the posterior lateral orbit from which exit sutures to allow adjustability of the length. Recognizing that there is a 2 to 1 variation in the normal forces in individuals,(2) this adjustability is an essential element, since calculation alone cannot be ultimately sufficient in the clinical application.

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