Extraocular muscle forces in normal human subjects

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Actively developed horizontal muscle forces and tissue stiffnesses were measured in 29 normal orthophoric volunteer subjects (18 to 33 years old) by means of noninvasive length-tension forceps. Mean active fixation force developed at 50 deg extreme gaze was 26% greater for the medial rectus (74.8 gm) than for the lateral rectus (59.1 gm). The variation of maximum active force among individuals was 2:1 (48 to 103 gm). These muscles developed up to 25% of their maximum active force out of their field of action. Active (counter) hysteresis force differences of over 10 gm were measured between nasal and temporal gaze directions. This study suggests that a muscle which develops a maximum active force of less than 45 gm would be suspect as paretic. Variations from the normal pattern of reciprocal innervation, reflected in the graded, active force of individual muscle contraction, may help in understanding some types of oculomotor pathology. The mean tissue stiffness—restraining movement of the globe in the nasal direction (1.05 gm/deg) is 11% greater than in the temporal direction (0.94 gm/deg). This is consistent with a stronger medial rectus balanced by a greater load. Variation of stiffness of 2:1 was observed among individuals; 0.8 to 1.7 gm/deg pulling nasally and 0.77 to 1.2 gm/deg temporally. Passive hysteresis and viscous force differences of over 10 gm were observed between the passive forced pull and normal spring-return of the eye. Large stiffnesses may be normal if balanced by large active forces. Abrupt changes of the length-tension curve indicate the magnitude and location of restrictions.

Key words: length-tension, active force, stiffness, hysteresis, reciprocal innervation, restrictions

Accurate information is needed on the active and passive forces that are present at a given positioning of the eyes. Strabismus diagnosis and surgical planning benefit from knowing the magnitude of the actively developed forces of each muscle as well as the balance of agonist and antagonist active forces.

We also need to know the normal load (stiffness) that must be overcome to move the eye from a certain eye position. This information can be useful when making a differential diagnosis of the strabismus disorder and can aid in decisions regarding surgical management.

Most reported load (stiffness) values or active muscle forces are in one direction only or are unaccompanied by data on the relaxing antagonist muscle force acting against the agonist force. In addition, much of this data is from strabismic eyes, possibly nonrepresentative of normal subjects. There is an obvious need for such information from a comprehensive sample of normal individuals.

Using normal subjects, we have measured the magnitude of active (isometric) force de-
Fig. 1. Length-tension forceps as used with a subject. Electronic strain gauges in the forceps shanks measure force. Note the forceps grasping the nasal limbus. A small loudspeaker (ultrasonic pulse source) mounted on the frame of a pair of glasses can be seen. Time of flight of sound from loudspeaker to a microphone mounted above the tip of the forceps is proportional to the distance of the forceps from the source (fixed on the head).

Developed separately by the medial rectus muscle and by the lateral rectus muscle during fixation in horizontal gaze. We have also measured the magnitude of the load (stiffness) that these muscles must overcome to move the eye in each direction.

These data provide a quantitative baseline of the active and passive forces acting on a normal eye. In a patient with strabismus, differences from these values aid in making a differential diagnosis resulting in more accurate quantitative planning of strabismus surgery.

Methods and protocol

We have measured 29 normal volunteer subjects ranging in age from 18 to 33 years. They showed no pathological conditions. All were within 2° of being orthophoric.

A newly developed clinical technique previously described was employed for assessing and recording the individual medial and lateral rectus active muscle force as a function of eye position over a 100 deg range of horizontal gaze. The load (stiffness) of the orbital tissues was also determined over a 60 to 100 deg range of eye position. The technique utilized a specially instrumented forceps to obtain a measurement of force (up to 110 gm) and forceps-positioned eye displacement (up to 20 mm).

The forceps employed were the large Pierce straight fixation forceps (Storz Model E1942-13). The broad tip of the forceps permit a firm grip of the limbal conjunctiva. The shanks of the forceps tip were milled to a width of 0.7 mm for a distance of 15 mm up the shank. Semiconductor strain gauges were mounted on these narrow beams to measure any force applied at right angles to the long axis of the forceps. The force required to rotate the globe or the force applied by muscles to the globe as the forceps held the globe in a fixed position could then be measured. Force readings were linear within ±2% over a ±150 gm range. Hysteresis was less than ±0.50 gm after ±100 gm of load had been applied. A small microphone with an opening near the tip of the forceps detected inaudible sound pulses from an ultrasonic source attached to the head of the subject. This ultrasonic device served as a sonar system and provided a constant indication of the distance between the ultrasonic source and the forceps tip. Because the ultrasonic source was fixed on the head, a measure of eye position was obtained from a knowledge of the forceps tip location. Position accuracy was within ±3% over the range of ±50 deg of eye position.

This noninvasive forceps and ultrasonic sound
Fig. 2. Length-tension forceps protocol for left eye measurements. A, Subject maintains 30 deg right fixation with right eye. The left eye is slowly (10 deg/sec) rotated temporalward and returned several times. The resulting load (stiffness) record represents the resistance to temporal rotation of the eye. B, Forceps hold the left eye steadily at a 50 deg temporalward rotation as subject tracks a slowly (10 deg/sec), smoothly moving target from 50 deg left to 50 deg right and return with the right eye. A plot of actively developed force, $F_M$, of the isolated left medial rectus muscle as a function of gaze effort can be determined. C, A mirror image of A results in the load (stiffness) for nasal rotation. D, Mirror image of B results in the active force, $F_L$, of the isolated left lateral rectus muscle as a function of gaze effort can be determined.

source are shown in Fig. 1. The source of ultrasound can be seen mounted on the frame of a pair of glasses. The ultrasonic source may also be mounted on a headband, with a flexible piece of heavy copper wire to permit adjustment for proper location (approximately 2 inches temporal to the outer canthus of the subject's eye). The ultrasonic source provides a sound field immediately in front of the eye. This permits the position of the eye (forceps tip) to be monitored continuously with force measurements over a 100 deg range of eye position.

The forceps are held perpendicular to the globe at all times in order to obtain proper readings of force and position. An error in the recorded force can result from misalignment. If the forceps are held within ±15 deg of the perpendicular to the surface of the globe, the geometrical cosine error is within 3% for force and position readings. A separate observer checked that the forceps were held within this angle at all times. During a typical stiffness measurement, force and position errors tend to cancel each other, further ensuring reliable measurements.

An X-Y oscilloscope was used to display force as a function of eye position. This instantaneous display of data enabled us to determine whether the data were in the expected range, were reasonably linear, and were free of artifacts. If not, the measurements were immediately repeated for confirmation. These data were simultaneously recorded on a multitrack FM tape recorder for later playback on an X-Y chart recorder to provide a permanent record.

From the family of innervated length-tension curves of oculorotary muscle it can be shown that active and elastic forces operate independently of each other and can be separately measured. In this study we measured the stiffness associated with innervated muscles, not passive muscles, perse. If the muscle innervation remains constant, then the force changes due to varying the length of the muscle are elastic in nature as seen from the constant slope of the length-tension curve. Conversely, force changes made with a constant muscle length are active in nature (are due only to changes of innervation). These separate active and elastic force components can be simply added to arrive at the total force acting on the eye.

It has been previously determined that the ac-
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Fig. 3. Load (stiffness) record for a temporal rotation of an intact, normal human left eye measured in Subject K. C. The left eye was abducted from 30 deg nasal to 45 deg temporal, returned to 30 deg nasal, and repeated with the length-tension forceps. The average load stiffness, \( K_T \), for this temporalward pull is 0.86 gm/deg. Although low, this stiffness is within 9% of the mean value for all subjects in this study. On the return pull near the 30 deg nasal duction position, the subject attempted a saccade to the right.

tive force of an individual medial or lateral rectus muscle can be effectively isolated and measured by eliminating contributions of its antagonist over most of its range of innervation. To do this, the subject is requested to fixate a target at extreme gaze. The eye is then pulled beyond this extreme-gaze position and held rigidly fixed with the forceps. The "excluded" muscle can thereby be shortened to the point that it is slack. Even while innervated, as long as the muscle is in a slack condition, by definition it exerts no tensile force. Therefore, as the subject is directed to track a known target with the opposite eye, the force recorded by the forceps is essentially due to the isometrically extended agonist muscle. The antagonist muscle may in some instances contribute a small force change if not entirely slack near the zero force region of the measured muscle.

By Hering's Law, innervation of the right eye will be accompanied by similar innervation of the yoke muscles of the left eye. Consequently, a plot of left eye active muscle force as a function of gaze effort (attempted eye position) can be determined by monitoring right eye position, as in Fig. 2, B and D. The right eye (target) position signal is used to deflect the horizontal axis, and the measured force from the left eye is used to deflect the vertical axis of an X-Y oscilloscope or X-Y plotter.

The protocol followed in this investigation is now described. The tension developed by the left eye is measured in all subjects. Topical anesthesia drops (proparacaine hydrochloride, 0.5%) are instilled in the subject's left eye. The force and displacement channels of the length-tension forceps are zeroed. Fig. 2 illustrates the protocol employed.

1. For a measurement of the orbital load due to a temporal rotation, the subject is directed to fix the gaze of his right eye on a 30 deg right target (Fig. 2, A). The nasal limbus of the left eye is grasped with the forceps. The left eye is then slowly rotated from its 30 deg right position temporally to 30 deg or more left and returned to its starting position. This slow (10 deg/sec) duction movement results in a graphic plot of the load
Fig. 4. Record of the active force, $F_M$, developed by the left medial rectus muscle of Subject K. C. Upper curve, Agonist activity; lower curve, active antagonist graded relaxation force. Both are functions of gaze effort.

(stiffness) characteristics of the left eye, as shown in Fig. 3. The procedure is performed two or three times. The length-tension characteristics represent the stiffness of the combined orbital tissues constituting the load the extraocular muscles must move, particularly in the temporal field of gaze. We chose the 30 deg position for fixation rather than the primary position in order to obtain an uninterrupted measurement of stiffness over a large range of gaze extending through the primary position.

2. To measure active medial rectus force, the left eye is held steadily in the extreme 50 deg abducted position while the subject tracks a smoothly moving target with his free right eye (Fig. 2, B). The target is a small bright red spot projected from a 0.3 mm helium-neon laser source and is moved electronically (by a triangle wave) from the 50 deg left gaze position at a constant rate of 10 deg/sec to the extreme 50 deg right gaze position and is then returned. This procedure is performed two or three times. The left eye is then released, and the subject is permitted to rest.

Plotting force measured from the left eye vs. right eye position results in a graph of the active force pattern of the left medial rectus muscle as a function of gaze effort, as shown in Fig. 4. This isometric, active force is directly proportional to medial rectus muscle innervation.

During the foregoing procedure, the left lateral rectus muscle is foreshortened to a slack length. As long as it is slack, it will not deliver force to the measuring forceps. Thus the isometric, extended medial rectus muscle may be effectively isolated over most of its range of innervation, and therefore its actively developed force can be assessed.

3. The orbital load for a nasal rotation is obtained in a similar fashion to that of Fig. 2, A, but in mirror imagery (Fig. 2, C). The subject fixates a target at 30 deg left with his right eye. The temporal limbus of the left eye is grasped with the forceps, and the left eye is slowly moved nasally from 30 deg left to 30 deg or more right and returned. This procedure is performed two or three times. The procedure measures the load (stiffness) of the left eye, particularly into the field of action of the left medial rectus muscle. The resulting length-tension characteristics represent the stiffness of the orbital tissues constituting the load the medial rectus muscle must move, as shown in Fig. 5.

4. The active lateral rectus muscle force is
obtained in a similar fashion to that of Fig. 2, B, but in mirror imagery (Fig. 2, D). As the left eye is firmly held in the 50 deg adducted position, the subject tracks the steadily moving target with his right eye from 50 deg gaze right to 50 deg gaze left and back again, repeating the constant velocity (10 deg/sec) tracking movements through two or three cycles. At the end of a cycle when the right eye is once again looking 50 deg right, the left eye is released, and the measurements are done. This procedure measures the isolated left lateral rectus muscle active force as a function of gaze effort, such as shown in Fig. 6.

Results

All the active force and load (stiffness) records shown in the figures of this report were purposely chosen from a single typical subject (K. C.). This permitted a direct comparison of the active force as well as the length tension characteristics of the medial and lateral rectus muscles within the same subject.

Tissue stiffness. Fig. 3 is a record of the data resulting from a forced rotation with the length-tension forceps. The “noise” on the force channel was due primarily to tremor of the eye, plus some contributed by tremor of the forceps holder’s hand. The measured stiffness in the temporal field for Subject K. C. could be seen to be 0.86 gm/deg ($K_T$ in Table I). Stiffness is defined here as the slope of the length-tension curve as the eye is pulled away from the equilibrium or zero net force position. Note that the stiffness measured during the return phase was essentially the same as that measured during extension. Successive pulls resulted very closely in the same measured forces, providing confidence in the method and credibility of the results of tissue load (stiffness) measurements (Fig. 3).

Fig. 3 shows two successive pulls (above) and one return phase (below). Note that the measured force during the return phase was considerably less than on the pulling phase. This force difference was due to viscosity and hysteresis caused by internal friction. Hysteresis is defined as a retardation of displacement when the direction of force acting upon a body is changed. In this example the
Fig. 6. Data comprising a record of the active force developed by the left lateral rectus muscle, \( F_L \), as a function of gaze effort (right eye position) in the intact eye of Subject K. C. Upper curves, as the muscle acted as an agonist; lower curves, during graded relaxation of the muscle as an antagonist. 1.5 cycles of activity are recorded.

effects of viscosity and hysteresis could be clearly seen as the nearly constant force difference (of about 12 gm) between the extension and return phase. A greater force difference was seen with faster rates of pull and return due to viscosity. To reduce effects of viscosity we pulled the eye at a low rate, about 10 deg/sec (2 mm/sec). Physiological data indicate that the viscous force is about 3 gm when oculorotary muscles are pulled at 10 deg/sec. Thus in each direction the viscous and hysteresis forces were about equal, 3 gm each, for 6 gm total in one direction and 6 gm in the opposite direction.

Fig. 5 is a record of the load data obtained by rotating the left eye nasally to about 40 deg while the right eye maintained fixation on a 30 deg left target. Two successive nasal pulls could be seen to virtually coincide. The stiffness of the tissue load was 1.1 gm/deg (\( K_N \) in Table I). There was also a force difference due to hysteresis and viscosity of 10 to 15 gm during the return phase, particularly in the nasal field, which is the field of action of the medial rectus muscle. Fig. 7 permits direct comparison of the separate loads (stiffnesses) associated with rotation of the eye, first temporally and then nasally.

Table I shows the results of stiffness measurements for temporal pulls (\( K_T \)) and for nasal pulls (\( K_N \)) for each of the 29 normal subjects in this study. A standard t test on individual pairs of stiffness values showed a significant difference (\( p = 0.01 \)). It will be noted that the mean stiffness when the eye was rotated in the nasal direction (1.049 gm/deg) was some 11% greater than the stiffness when the eye was rotated in the temporal direction (0.942 gm/deg). This indicates that a greater active force was required to rotate the eye in the nasal direction than in the temporal direction. This would suggest that to maintain comitancy (both eyes pointing in the same direction) during eye rotations, the...
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Fig. 7. Load stiffness records of the left eye of a normal subject (K. C.). The record sloping up to the right on the graph represents the force required to pull the intact, covered left eye temporalward. The slope of this curve, $K_T = 0.86$ gm/deg, represents primarily the stiffness of the left medial rectus muscle and associated passive tissues restraining globe motion in the temporal direction. The record sloping up to the left on the graph represents the force required to pull the intact, covered left eye nasallyward. The slope of this curve, $K_N = 1.1$ gm/deg, represents primarily the stiffness of the left lateral rectus muscle and associated passive tissues restraining movement of the globe in the nasal direction. The large asymmetry of stiffness in the two directions of gaze is clearly evident in these records, and $K_N$ was greater than $K_T$ in 24 of 29 normal subjects.

The medial rectus muscle must be "stronger" than the lateral rectus muscle.

S.E.M.'s were less than 5% of the mean value for nasal rotations and less than 3% of the mean for temporal rotations. The individual variation of tissue stiffness was approximately two to one as found in this normal population. The variation was 0.8 to 1.7 gm/deg for nasal rotations and 0.77 to 1.2 gm/deg for temporal rotations.

Active muscle forces. The active force due to an effectively isolated, isometric left medial rectus muscle as a function of eye position is presented in Fig. 4. The upper curve shows the active force when the medial rectus muscle functioned as an agonist, and the lower curve shows the graded release of active force while the medial rectus muscle was relaxing as an antagonist. There was some 10 gm greater force developed by this muscle when it acted as an agonist than when it acted as an antagonist. This force difference was nearly constant over the field of action of the muscle and up to 20 deg out of its field of action. (A muscle is said to be within its field of action when it is shorter than primary length, i.e., the length when looking straight ahead.) When functioning as an agonist, the maximum sustained fixational force developed by the medial rectus muscle of this subject was about 68 gm. The observed transient peaks to 73 gm may be associated with saccadic refixation. Inadvertent small movements of the forceps were continuously monitored by means of the sonar length-detecting system, and representative active force records were selected only when forceps movement was less than 0.5 mm, e.g., Fig. 4.

The actively developed force data from the isometric left lateral rectus muscle of Subject
Fig. 8. Single traces of the active force measured in Subject K. C. from the left lateral rectus muscle (sloping up to the right) and the left medial rectus muscle (sloping up to the left). Both of these records represent active force with the muscle acting as an agonist. Nasal gaze effort is left on the graph, temporal to the right. The maximum medial rectus active muscle force is seen to be about 70 gm, whereas the maximum lateral rectus active muscle force is about 50 gm. The nonlinear character of the active force as a function of gaze effort is clearly seen for each muscle, with only 25% to 30% of the total active force being developed at the primary position and active force balance occurring at 12 to 15 deg temporally.

K. C. are shown in Fig. 6. The magnitude and shape of the active force curves were consistent over a number of cycles of right eye movement from 50 deg nasal to 50 deg temporal rotation. When the lateral rectus muscle was acting as an agonist, its maximum sustained active fixational force was 50 gm, with transient saccadic refixation peaks to 55 gm. Again, there was some 10 gm greater active force developed by the lateral rectus muscle when acting as an agonist than when acting as an antagonist over the entire 100 deg range of muscle activity.

Fig. 8 plots on the same graph, for direct comparison, the active force data of the medial and lateral rectus muscles. It can be seen that an oculorotatory muscle was able to exert a considerable amount of its active force (up to 25% of maximum) outside of its field of action. The active forces of the medial and lateral rectus muscles were not equally balanced at primary gaze but instead at about 12 to 15 deg of temporal gaze.

In general, for any gaze position, the medial rectus muscle acting as an agonist develops more force than the lateral rectus muscle acting as an agonist. For Subject K. C. the maximum medial rectus active muscle force was about 70 gm vs. about 50 gm for the lateral rectus muscle (Fig. 8). This represents a 40% greater maximum active force for the medial rectus.

Fig. 9 graphically compares the maximum active forces developed by the medial and lateral rectus muscles of each of the subjects in this study. The mean of the maximum active force of the medial rectus muscle was 74.83 gm (range of 48 to 103 gm) with an S.E.M. of 2.7 (Table 1). The mean of the lateral rectus maximum active muscle force was 59.14 gm (range of 45 to 92) with an S.E.M. of 2.3. The average value of the maximum
active medial rectus muscle force was 25% greater than the maximum active lateral rectus muscle force. The maximum active force developed by the lateral rectus muscle was on average about 15 gm less than that of the medial rectus muscle. The active force developed by the medial or lateral rectus muscle was greater than 45 gm for all the subjects measured. A variation of maximum active force among individuals of two to one is seen in this study.

There was no clear correlation between developed tension and age within the narrow age range of these young adults.

**Discussion**

A detailed knowledge of normal active muscle forces and passive forces restraining rotation will permit quantitative verification of existing theories of eye movement and may permit further development of oculomotor control theory and its attendant models that will lead to a clearer understanding of the mechanisms of eye movements and the underlying causes of strabismus.

We have determined the normal range of the actively developed, individual, isometric force for the medial and lateral rectus muscles and the magnitude of the load (stiffness) moved by these muscles by means of a newly developed length-tension forceps. This technique should permit differentiation between passive mechanical restrictions and innervational imbalances.
Fig. 10. Net active force rotating the globe temporally is the active force of the lateral rectus muscle acting as an agonist, \( F_{\text{L,ag}} \), minus the active force of the medial rectus muscle acting as an antagonist, \( F_{\text{M,antag}} \), as taken from Figs. 6 and 4, respectively. This net active force is plotted as \( F_{\text{L,ag}} - F_{\text{M,antag}} \) and is responsible for moving the temporal load of the intact eye, \( K_T \times \theta \), as taken from Fig. 3, all from Subject K. C. The two curves match remarkably well and give credence to modeling techniques utilizing clinically derived force measurements. The subject, as indicated by this model result, was essentially orthophoric (see Fig. 11).

The results (Table I) are in good agreement with previously reported values for strabismus patients.\(^5-9\) Our data will provide a useful baseline of the orbital mechanical forces existing in normal individuals. Differences from these values in strabismus patients will aid in the differential diagnosis of their disorder and in more accurate quantitative planning of strabismus surgery. The maximum active force of individual oculorotary muscles may be useful in the diagnosis of paralytic strabismus. In our investigations, the normal maximum active muscle force of the medial and lateral rectus muscles was greater than 45 gm. Therefore a maximum active force of less than 45 gm would make one suspect that the muscle was paretic. In a clinical sense, a horizontal rectus muscle with a force greater than about 30% of normal maximum (or above 20 gm) can make significant contributions to eye rotation. A horizontal rectus muscle force less than 25% of normal maximum, or 15 gm, is functionally paralyzed and would not exert sufficient force to contribute significantly to eye rotation.

The shape of the actively developed force vs. eye position curve leads us to an understanding of otherwise hidden mechanisms of strabismus, for example, Duane’s syndrome with paradoxical innervation. The pattern of active muscle force vs. gaze position for the medial and lateral rectus muscles (Fig. 8)
clearly shows the pattern of reciprocal innervation. As the force of one muscle increases, the force applied by its antagonist decreases. This nonlinear pattern resembles data derived from horizontal rectus muscles of awake patients at surgery.\textsuperscript{5, 6} Such curves have proved useful in rigorously defining the innervational input pattern of oculomotor system models.

Our results show the mean load stiffness for all 29 subjects to be 1 gm/deg. This value is somewhat lower than that reported by Robinson\textsuperscript{1} (1.2 gm/deg) and by Childress and Jones\textsuperscript{2} (1.25 gm/deg) for eye movements of 5 deg or less. Their higher values of stiffness may be due in part to the additional force of hysteresis. This would be particularly true if the measurements were made after returning to primary from abduction each time. Childress and Jones\textsuperscript{2} reported a lower value, 0.65 gm/deg, for forced traction of the eye with movements in excess of 5 deg. Slight slippage of the contact lens at the higher forces may have contributed to their lower values.

Other studies have demonstrated that orbital stiffness (the slope of the load curves) is independent of the active force produced by tonic activity of the oculorotary muscles.\textsuperscript{2, 3}\textsuperscript{5} Thus the load curve determined at one fixed eye position appears to shift horizontally as the fixed eye position is changed, so that the point on the stiffness curve at which oculomotor forces balance corresponds to the present fixed eye position. This property is utilized in the following model calculations.

The active and passive forces measured in this study were used as inputs for a mechanical model of the oculomotor system.\textsuperscript{9} The net effective force rotating the globe was the active force-difference of the medial and lateral rectus muscles at each corresponding position of gaze. For temporal gaze the active force of the medial rectus muscle acting as an antagonist (lower tracing in Fig. 4) was subtracted from the active force of the lateral rectus muscle acting as an agonist (middle and upper tracings in Fig. 6). This results in a net active force-difference which acts against the load (stiffness) restraining temporal rotation of the globe (Fig. 10). The active force-difference curve matches remarkably well the measured load stiffness that the active force must overcome in temporal gaze. Of course, this is the expected theoretical result, but it is remarkable that the agreement is so good, considering the many exigencies of clinical data collection procedures. In Fig. 10 the left eye positions result in concomitance with the right eye within 2.5 \( \Delta \) over the entire 80 deg range of gaze over which stiffness of the left eye was measured. (Concomitance is defined as both eyes tracking together.) The calculated phoria of each eye position is depicted on a concomitance chart in Fig. 11. Comitance for this subject (K. C.) measured to be within 2 \( \Delta \), lending credence to the computational methods and model approach.

Stiffness measurements made on the intact eye are probably a more valid indicator of the load presented to the muscles as they occur in real life than those made at surgery. There is a question whether changes in stiffness may be produced by the trauma of surgery. There are also unanswered questions about the cross-coupling of globe-restraining tissue stiffness and muscle stiffness when attempts are made to measure these values separately at surgery.

Our measurements of the stiffness of the intact eye provide the actual load that the muscles must move to rotate the eye. This load is the sum of the muscle and globe-restraining tissue stiffness. We cannot measure noninvasively how much of this stiffness is due to passive muscle components and how much is due to the other passive orbital tissues restraining globe motion. From our previous investigations at surgery, we can estimate that some two thirds of this stiffness is due to muscle tissue.\textsuperscript{5, 6} In order to separate the contributions of stiffness due to muscle and to the passive globe-restraining tissues, it proves necessary to measure the passive load at surgery before and after the oculorotary muscles are disinserted. We are currently obtaining such data.

In most of the normal subjects we have measured, the length-tension (stiffness) characteristics for abduction and adduction were \textit{not} symmetrical. Data from the subject K. C.
in Fig. 7 show a 30% greater stiffness measured in the nasal direction (adduction). The active force data show the medial rectus muscle to be 40% stronger than the lateral rectus. Thus a stronger active medial rectus force is present to act against the greater load stiffness which resists adduction. The oblique muscles are also stretched in adduction and may be partly responsible for this asymmetrical load stiffness.

Although there is a difference in the nasal and temporal stiffness of the intact eye, all the load stiffness curves have been found for the most part to be linear (straight lines). Therefore discontinuities in the load curve (an abrupt change of stiffness) at some gaze position would indicate a restriction, contracture, or other pathological condition. Measurement of tissue stiffness over the entire range of eye movement can contribute important knowledge to the type, magnitude, and location of restrictions. It appears that a large stiffness may be normal if associated with large active muscle forces.

The length-tension forceps can be a useful instrument for quickly and simply making quantitative records of the passive and active forces responsible for positioning the eyes. This forceps permits a detailed analysis of active muscle forces and tissue stiffness to be plotted in each direction of gaze. Measurements of imbalances in the active muscle forces and asymmetries of load stiffness characteristics that resist eye movement offer the surgeon a useful quantitative tool for dealing with the difficult task of balancing forces involved in strabismus.

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