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A COMPARISON OF DIFFERENT MODELS OF EXTRAOCULAR MUSCLE COOPERATION

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Abstract—Different assumptions about the way in which the extraocular muscles act have been evaluated by comparing a set of models of extraocular muscle cooperation, each of which differ by just one assumption, against clinical data from patients with isolated nerve palsies.

INTRODUCTION

The study of the actions of the extraocular muscles has been given a fresh impetus by the work of Robinson (1975) on the mechanics of the extraocular muscles. Robinson has incorporated the results of experimental studies of the muscle forces acting on the eye and theoretical studies on the axes about which the muscle forces act in a model of the actions of the extraocular muscles. The model entails assumptions about the way in which the force exerted by each muscle changes with the length and innervation of the muscle, and assumptions about the axis of rotation of each muscle for a given position of the eye. These assumptions have been assessed in a previous investigation by Clement (1982). The aim of this study was to compare how well versions of the model with different underlying assumptions relate to clinical data on patients with isolated nerve pareses.

THEORY

The approach adopted here is that if only one assumption is changed in the model of Robinson (1975), then any changes in the behaviour of the model may be attributed to this assumption. Individual assumptions were only changed when there was either theoretical or experimental evidence for an alternative. The six versions of the model that resulted from this criterion were as follows:

(a) *Model 1*

The model defined by Robinson (1975).

(b) *Model 2*

The same as model 1 with the exception that each muscle follows its mechanical shortest path and acts around the corresponding axis.

(c) *Model 3*

The same as model 1 with the exception that each muscle acts around an axis fixed with respect to the head. The axis was taken to be perpendicular to the muscle plane with the eye in its primary position.

(d) *Model 4*

The same as model 1 except that the relative muscle strengths were taken to be proportional to muscle volume rather than cross sectional area. The volume of each muscle was calculated by approximating each muscle by a set of cylinders. The diameter of each cylinder was given by the average of the diameters of the muscle in successive anatomical sections, and the length of each cylinder was given by the distance between successive sections. The anatomical data of Nakagawa (1965) was used. The relative strengths of the muscles obtained by this procedure are as shown:

LR	MR	SR	IR	SO	IO
1.0	0.95	0.69	0.81	0.32	0.35.

(e) *Model 5*

The same as model 1 except that the reciprocal innervation function was taken to be:

$$E(\text{antagonist}) = \{(5.5+90.0)^2/[E(\text{agonist})+90.0]\}-90.0.$$

This results in the tension in a normal muscle reaching a minimum 15 degrees out of its field of action in accordance with the experimental findings of Collins *et al.* (1975). The assumption used by Robinson (1975) results in the tension in the muscle reaching a minimum in the primary position.

(f) *Model 6*

The same as model 1 except that there was no

passive force acting against the torsional movement of the eye.

The natural way of implementing a binocular model is to calculate the innervation values required by the muscles of the fixating eye, to apply these innervation values to the corresponding yoke muscles in the nonfixating eye and then to determine the position adopted by the nonfixating eye. However, when considered from the point of view of mechanics, it becomes apparent that the corresponding yoke muscles have different axes of rotation and different strengths, so that the nonfixating eye will adopt a different position from the fixating eye, even when both eyes are nonparetic.

France and Burbank (1978) have proposed the following computational scheme, which involves passing the innervation indirectly:

(1) Calculate the innervation values required by the Actual fixating eye (which may or may not be paretic).
(2) Calculate the position adopted by the Normal fixating eye with these innervation values.
(3) Calculate the innervation values required by the Normal nonfixating eye to reach this position.
(4) Calculate the position adopted by the Actual nonfixating eye with these innervation values.

Whilst this scheme is computationally effective it is open to the criticism that it does not reflect Hering's law of equal innervation. In particular, the scheme requires that when the fixating eye is paretic then it feeds abnormal innervation values into the nonfixating eye. It would be expected from the concept of the binoculus, as discussed by Hering (1868), that if the fixating eye did not reach a required position then the binoculus would supply the appropriate innervation to turn a normal eye in the direction in which the underaction is occurring. Consideration of this approach leads to an alternative computational scheme for binocular model as follows:

(1) Calculate the innervation values required by the Normal fixating eye (i.e. binoculus) for the specified gaze direction.
(2) Calculate the position adopted by the Actual fixating eye.
(3) If the actual fixating eye has not reached the specified gaze direction change the gaze direction of the binoculus, calculate the corresponding increase in innervation levels and repeat stage 2.
(4) When the actual fixating eye has reached the specified gaze direction, then the innervation values for the nonfixating eye are given by the innervation values required by the Normal nonfixating eye for the gaze direction of the binoculus.

The two schemes will be referred to as scheme A and scheme B, respectively.

METHODS

Case histories were chosen in which the patients had suffered a paresis of either the IV or VI nerve which had subsequently recovered. By selecting patients who subsequently recovered it was hoped to avoid the complications of contracture of the ipsilateral antagonist and subsequent underaction of the contralateral antagonist. In order to exclude the possibility that the muscle tissue itself was different from normal, any patients who had been diagnosed as diabetic were excluded from the study. In all, 15 patients were used, 5 or whom had IV nerve pareses and 10 of whom had VI nerve pareses. The patient group had an age range of 34 – 80 (mean = 65.6 years) and was comprised of 3 females and 12 males. All the Hess charts had been measured within 2 – 20 days of the attack.

The models were used to predict the effect of muscle pareses by scaling down the active tension produced by each muscle as proposed by Robinson (1975). The procedure for testing each model against the clinical data of each patient consisted of decreasing the muscle strength in steps of 10% and calculating a measure of the variation from the clinical data at each level of paresis. The measure of variation that was used consisted of the square of the angle, in degrees, between the gaze direction predicted by the computer and the gaze direction recorded on the patient's Hess chart. In order to provide a quantitative estimate of the match over all 9 positions recorded for each eye, the calculated values for the measure of variation at each position were summed, and these values are tabulated in the results section.

RESULTS

Examples of the behaviour of the six models are shown in Figs 1 and 2. In both cases the pair of Hess charts showing both the primary and secondary deviations have been calculated using scheme A. Figure 1 shows the predictions of the models when the lateral rectus of the left eye is producing only 50% of its normal active tension, whilst Fig. 2 shows the predictions when the superior oblique of the left eye is producing only 30% of its normal tension.

With respect to palsy of the lateral rectus it can be seen from the results of model 2 that if the muscles act around the shortest path then the ensuing pattern of eye movements differs from that with model 1. The predictions of models 3, 4 and 6 are virtually

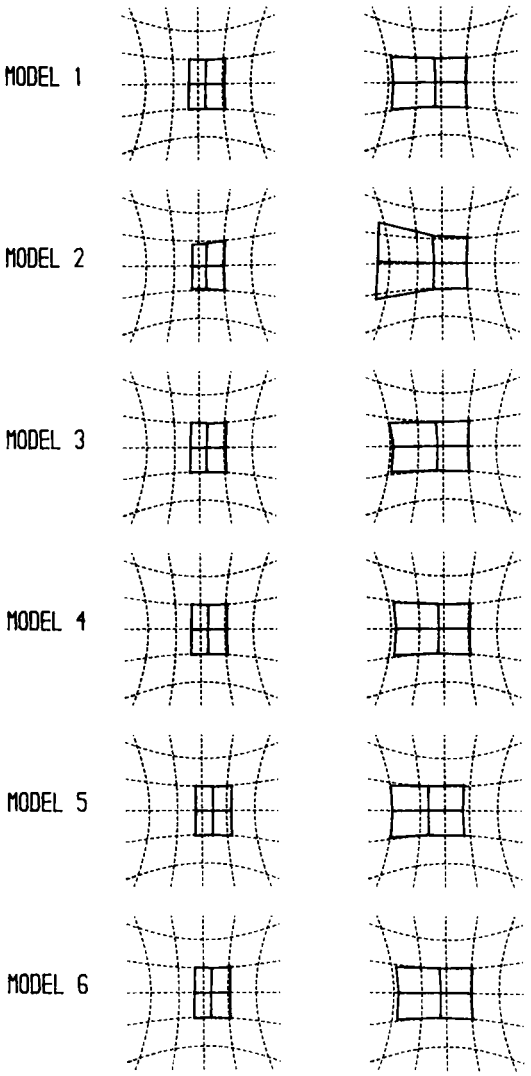

Fig. 1. Hess charts predicted by each of the models when the lateral rectus of the left eye acts with 50% of its normal strength.

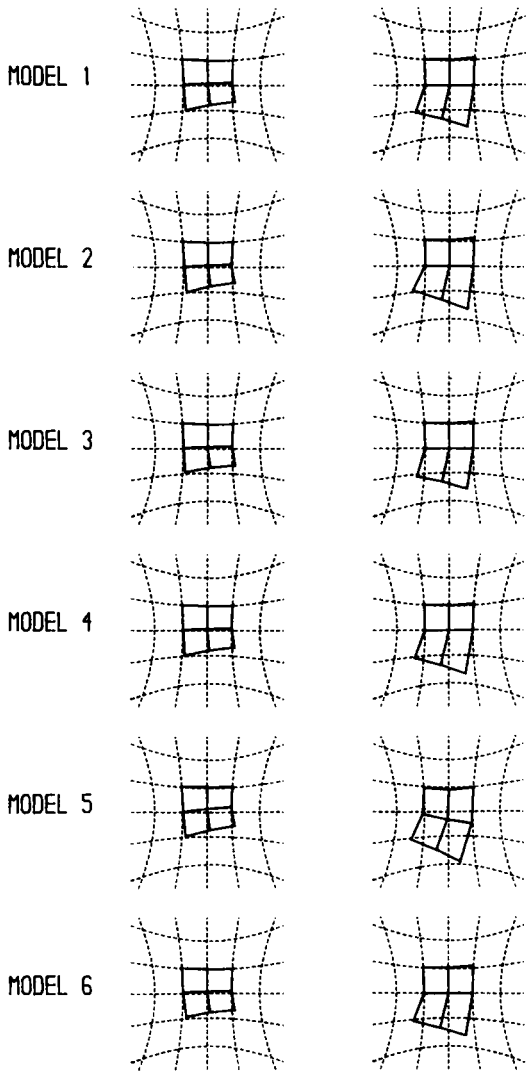

Fig. 2. Hess charts predicted by each of the models when the superior oblique of the left eye acts with 30% of its normal strength.

identical with those of model 1. However, model 5 shows that the change in ther reciprocal innervation function results in deviations of eye positions which occur both in and out of the field of action of the muscle. This is in contrast to model 1 in which the deviation occurs almost totally in the field of action of the muscle.

With palsy of the superior oblique, it was found that models 1–4 gave virtually identical results. Again model 5 was different in that it showed a deviation over a wider range of eye positions than did model 1. Not surprisingly, model 6 showed greater torsion than did model 1.

The clinical data for the nerve parese are shown in Figs 3, 4 and 5. The records have been arranged in order of increasing variation from the standard Hess chart positions. The variations of the predictions of each model from the clinical data are shown in Table 1. Initially, only the primary deviations were considered because of the additional assumptions needed to produce a binocular model. For both types of pareses, model 5 shows a considerable improvement over model 1. Model 6 performs as well as model 1 with sixth nerve palsy and somewhat better with fourth nerve palsy. Interestingly model 3 performed better than model 1 with fourth nerve

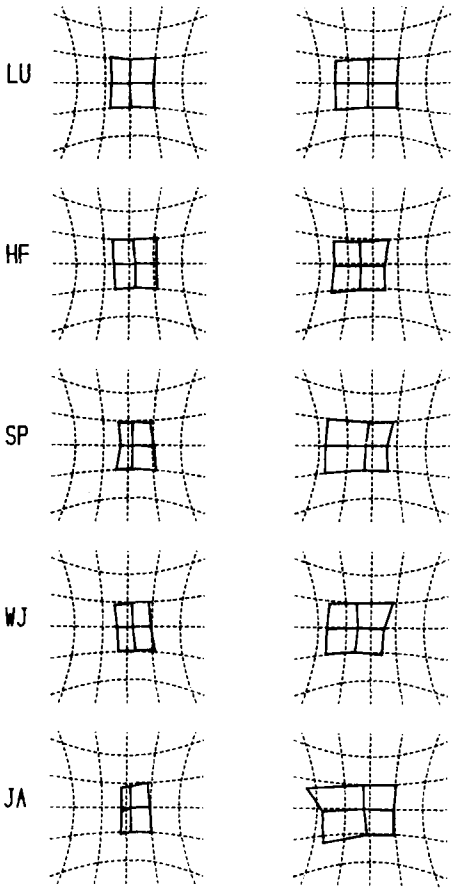

Fig. 3. Hess charts of 5 patients with paresis of the lateral rectus of the left eye. All the patient data is arranged in order of increasing variation from the standard Hess chart positions.

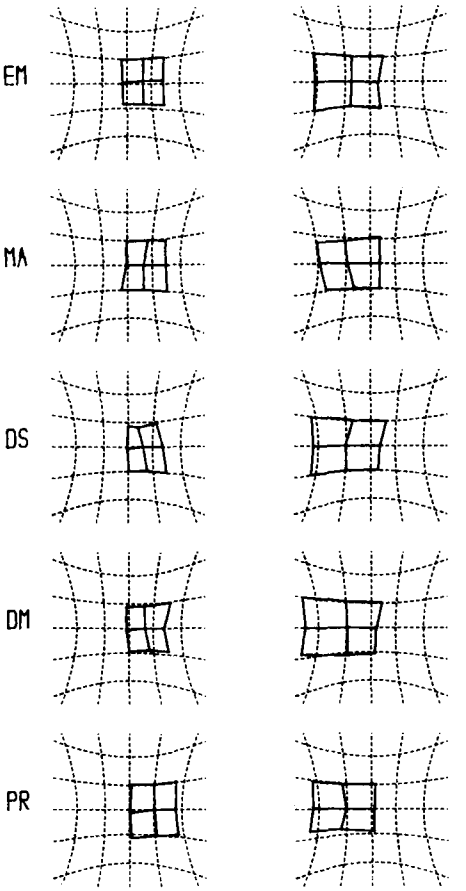

Fig. 4. Hess charts of the other 5 patients with paresis of the lateral rectus of the left eye.

palsy, although it did not perform as well with sixth nerve palsy. Models 2 and 4 both performed worse than model 1.

On the basis of these results it was decided that an improved version of Robinson's 1975 model could be produced by replacing the reciprocal innervation function used by him with the one tried out in model 5, and by removing the passive anti-torsion force, as tried out in model 6. In order to decide between the two computational schemes for modelling both the primary and secondary deviations two versions of the model were produced, each utilising one of the alternative computational schemes.

The variations of the predictions of each of the two computational schemes from the clinical data are shown in Table 2. For both the sixth and fourth nerve pareses scheme A performed better than scheme B, though the difference was most marked with fourth nerve pareses, where the match to the clinical data with scheme B was worse for the secondary deviation than with scheme A.

The validity of the final version of the model may be appreciated by noting that the values of the measure of variation of the clinical data from the standard Hess chart positions fell in a range from 198.8 to 4272.1 for the sixth nerve pareses and from 159.0 to 725.0 for the fourth nerve pareses.

DISCUSSION

The most surprising finding in the comparison of the six different versions of the model was how similar their behaviour was. This makes the task of modelling extraocular muscle cooperation easier, in that the predictions of the model remain valid despite alterations of the parameters in different individuals. Thus a change in the relative strengths of the muscles, as might reasonably be expected in different

Table 1. Variations of the predictions of the six models from the clinical data

	Model					
	1	2	3	4	5	6
LR Paresis						
LU	8.6	10.7	8.2	8.2	13.9	8.6
HF	9.6	15.8	10.4	10.2	4.1	9.7
SP	34.1	21.7	32.1	33.9	49.4	33.9
WJ	32.4	22.5	32.8	31.7	50.2	32.5
JA	59.3	36.6	57.8	56.7	100.4	58.1
EM	167.9	195.2	174.0	172.5	98.5	169.2
MA	165.6	215.1	170.5	174.3	85.6	164.9
DS	100.6	109.9	108.4	106.5	63.4	100.7
DM	190.0	217.8	199.7	198.4	109.0	190.2
PR	503.7	596.2	522.8	515.0	414.6	504.1
Means	127.2	144.2	131.7	130.7	98.9	127.2
SO Paresis						
DB	57.0	58.9	54.0	59.1	28.9	54.7
AC	82.0	86.4	78.9	83.8	73.4	83.4
EW	70.7	76.0	67.9	76.6	51.9	69.3
AB	115.3	119.2	104.1	124.2	94.1	104.3
SE	103.9	109.9	92.6	111.4	86.2	89.9
Means	85.8	90.1	79.5	91.0	66.9	80.3

Table 2. Variations of the predictions of the two binocular schemes from the clinical data

	Scheme A			Scheme B		
	LE	RE	Total	LE	RE	Total
LR Paresis						
LU	19.7	28.7	48.4	64.6	18.6	83.2
HF	33.4	99.7	133.1	33.4	103.1	136.5
SP	49.3	60.7	110.0	49.3	56.7	106.0
WJ	50.3	68.5	118.8	50.3	74.8	125.1
JA	99.5	181.1	280.6	99.5	182.2	281.7
EM	123.0	92.5	215.5	122.3	105.7	228.0
MA	142.5	168.4	310.9	142.5	186.0	328.5
DS	63.0	119.9	182.9	63.0	108.1	171.1
DM	109.0	149.5	258.5	109.0	157.9	266.9
PR	411.7	296.7	708.4	411.7	304.9	716.6
Means	110.1	126.6	236.7	114.6	129.8	244.4
SO Paresis						
DB	30.1	23.7	53.8	27.7	59.1	86.8
AC	73.0	113.3	186.3	73.0	169.5	242.5
EW	97.6	33.9	131.5	52.9	79.0	131.9
AB	154.5	60.5	215.0	72.1	104.7	179.9
SE	107.9	151.4	259.2	223.6	323.7	547.4
Means	92.6	77.6	169.2	89.9	147.2	237.1

individuals, did not produce radically different predictions. It was also interesting to note that the fixed axis assumption which has been argued for by Jampel (1970, 1975) provide a close match with the clinical data. From a purely computational viewpoint, this assumption simplifies the programming of the calculations.

For the computation of both primary and secondary deviations, scheme A produced a better match to the clinical data than did scheme B. However, this data did not test the difference between the way in which the two schemes pass cyclotorsion from one eye to the other. With a IV nerve palsy, both schemes predict excyclotorsion in

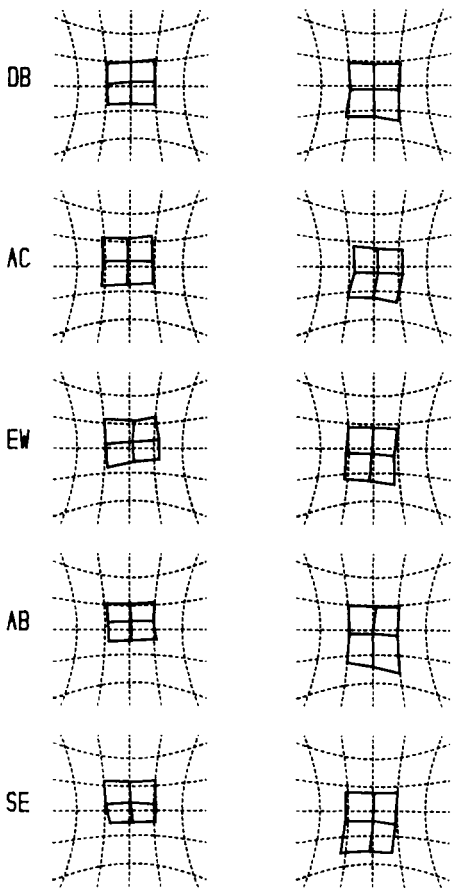

Fig. 5. Hess charts of the 5 patients with paresis of the superior oblique of the left eye.

the paretic eye when the nonparetic eye is fixating, but scheme A predicts greater excyclotorsion in the nonparetic eye, whilst scheme B predicts zero excyclotorsion in the nonparetic eye, when the paretic eye is fixating. In their study of excyclotropia of the nonparetic eye Olivier and von Noorden (1982) argued against excyclotorsion of the nonparetic eye, which suggests that further comparisons of these two schemes are necessary.

CONCLUSION

It has been demonstrated that, by making an alternative reciprocal innervation assumption and removing the passive anti-torsion force assumption, an improved version of Robinson's 1975 model of extraocular muscle cooperation can be produced, which leads to realistic descriptions of isolated nerve palsies.

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