SEE++: A Biomechanical Model of the Oculomotor Plant

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ABSTRACT: The consequences of changes in the oculomotor system on the three-dimensional eye movements are difficult to grasp. Although changes to the rectus muscles can still be approximately understood with simplified geometric models, this approach no longer works with the oblique muscles. It is shown how SEE++, a biomechanical model of the oculomotor plant that was built on the ideas of Miller and Robinson (1984) can improve the understanding of the effects of changes to the oblique eye muscles. By displaying only selected muscles, and by illustrating the relative contribution of these muscles through color-coding the bulb surface, the functional properties of the oblique muscles can be presented in a much clearer way. Investigating the effects of a hyperactive inferior oblique muscle shows that this type of model can help to clarify the functional cause of a pathology, which can otherwise be unclear, even for common pathologies.

KEYWORDS: extraocular muscles; oculomotor system; computer simulation; modeling

INTRODUCTION

Two factors determine the orientation of our eyes: the innervation of the extraocular muscles (EOMs), and the mechanical and physiological properties of the oculomotor plant. For purely horizontal eye movements close to the reference position, the geometry of the oculomotor plant is fairly simple. As a result, this type of eye movement has been used to investigate many aspects of the neural control of eye movements.2 When researchers tried to understand the contributions of the individual extraocular muscles during combined horizontal/vertical eye movements, things became more complicated.3 Although some have argued that the brain explicitly controls all three directions of eye rotations,4 others have claimed that the mechanics of the oculomotor system are such that only commands for the horizontal and vertical eye position need to be controlled explicitly.5,6

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Many biomechanical models supporting the more “mechanistic” view are based on geometrical abstractions. Testing their accuracy is sometimes possible, but then only for individual parameters. Anatomically more accurate models are generally derived from original ideas by Robinson. These ideas were developed further by Miller and integrated into the first visual computer model of the oculomotor plant, Orbit. Porrill, Warren and Dean wanted to study various aspects of this model, which required a model that could be run in batch simulations. For this they developed EyeLab, a simplified version of Orbit written in MATLAB.

As we wanted to eliminate some restrictions of Orbit, as well as add more flexibility in the visualizations, we collaborated with Miller and developed a new program, which we called SEE++. A detailed description of the technical details of SEE++ and of the biomechanical differences between the different models is under preparation.

METHODS

SEE++ incorporates a wide range of visualization tools, as well as different biomechanical “kernels.” As there are still discussions about the relative contribution of different parts of the oculomotor plant, the user can choose between different options: a “string mode,” where the extraocular muscles are represented by simple strings; a “tape mode,” which also includes muscle-stiffness (this makes a significant difference for the side-slip of the muscle at the insertion on the globe); an “Orbit mode,” which was made possible by Miller, who gave us full access to the source code of Orbit; and a full mode, which provides more accurate results for pathological eyes in eccentric eye positions.

SEE++ also allows the user to adjust the visualization to suit the current requirements. For example, in Figure 1 we have removed the face and all muscles but the superior oblique. Also, we have selected the shading of the globe to reflect the horizontal eye movement contributions of the superior oblique.

RESULTS

As the consequences of changes to the oblique muscles are much more difficult to understand than changes to the rectus muscles, we concentrate here on the obliques. In Figure 1 we show the left and right superior oblique (SO) muscle for a healthy subject, when looking 30° to the left. It is obvious that a contraction of the SO muscle of the right eye would lead to a downward movement of that eye, while on the left eye a SO contraction would mainly induce a torsional eye movement.

For a surgical correction of an oculomotor pathology it can be important to consider all three movement components of a muscle: horizontal, vertical, and torsional. In Figure 1 the horizontal component is color coded on the globes: insertion of the SO anywhere in the white area elicits no horizontal movement; insertion in the gray area elicits horizontal movements proportional to the gray level. Thereby horizontal is defined as ad-/abduction. Looking 30° to the left the SO of the right eye has essentially no horizontal movement component, whereas contraction of the left SO in-
duces a significant amount of horizontal eye movement (Fig. 1). Without visual indications, these insights are difficult to obtain.

As a result of the tilted insertions of the oblique muscles, a pathology caused by hyper- or hypoactivity of an oblique EOM, or by a pathological change in the muscle geometry of an oblique muscle, is difficult to understand. This can lead to confusion in the terminology of diseases.

For example, for a hyperactivity of the inferior oblique, which induces predominantly a vertical strabismus, different terminologies are used on the two sides of the Atlantic: whereas in Europe, especially in the German-speaking countries, both terms “strabismus sursoadductorius” and “inferior oblique overaction” are used, the English-speaking literature uses the expression “primary inferior oblique overaction” for both vertical motility disorders. Recently, these two expressions have been used almost synonymously.

A comparison of the definitions for these two types of strabismus shows that the two are different (Table 1), but the etiology is left unclear.

To find out the causal differences between these two pathologies, we tried to simulate them with SEE++.

**Strabismus Sursoadductorius**

To simulate strabismus sursoadductorius, we started with a lateral displacement of the functional origin (i.e., the pulley) of the inferior oblique muscle (IO), com-
bined with an increase in the muscle force generated by innervation. (For the current simulations, we doubled the active muscle force.) In addition, we sometimes added a small lateral displacement of the functional origin of the superior oblique. This produced the excyclorotation typically observed in patients with strabismus sursoadductorius. The exact choice of the parameters depends on the specific magnitude of the eye movements of the patient under investigation. An example screenshot of the resulting SEE++ display is presented in Figure 2.

**Inferior Oblique Muscle Overaction**

We were surprised to find that the eye movement patterns found in patients diagnosed with “IO overaction” could not be simulated solely with an increase in the active force of the IO: an additional medial displacement of the inferior oblique...
insertion was necessary. To reproduce the observed patterns, we also had to choose a lateral displacement of the superior oblique muscle insertion. Again, the exact magnitude of the parameters depends on the individual case.

DISCUSSION

Investigations of the neural control of eye movements, as well as of the mechanical contributions of the oculomotor plant, have concentrated on small horizontal or vertical eye movements around the primary position. For such movements, an intuitive interpretation of pathologies of the oculomotor plant can often lead to acceptable results. But for arbitrary three-dimensional eye positions, the complexity of the oculomotor plant is too large for a reliable interpretation of the cause of oculomotor disorders. As a result, the naming of oculomotor pathologies has been in some cases purely descriptive and sometimes somewhat arbitrary. We believe that an etiologic naming of pathologies could facilitate the understanding of pathologies, and could also reduce intercontinental naming incompatibilities.

In the example presented above, this inconsistency in classification has no negative consequences for the patients. Although strabismus sursoadductorius and inferior oblique muscle overaction are different, they are treated in the same way: in both cases a recession of the inferior oblique muscle on the affected eye is recommended. In the future, a systematic application of advanced, realistic computer models to the investigation of oculomotor pathologies might improve our understanding of diseases, and thus help to optimize the chosen treatments.

REFERENCES