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PERSPECTIVE

Instead of pulley bands, does retrobulbar fat keep the eye muscle bellies in place and thereby act like a pulley?

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ABSTRACT
Extraocular muscle pulley bands were described by Tenon in 1805 as “faisceaux tendineux” acting as “poulies de renvoi.” The Passive and Active Pulley Hypotheses propose that these connective-tissue bands between muscle and bony orbital rim limit vertical shift of the horizontal rectus muscle belly in up- and downgaze, caused by the muscle’s tendency to assume the shortest path from origin to insertion. The band’s attachment to the muscle moves 20 mm sagittally when the eye looks from 50° left to 50° right, however, impeding vertical muscle stabilization. Sliding of the muscle in a sleeve would permit sagittal movement, but four anatomical studies could not confirm that. The band would have to be elastic: We measured it after orbital exenteration and found it to be slack, however, and once extended, very stiff. Our research group in Amsterdam suggested in 1984 that the retrobulbar fat and its enveloping connective-tissue sheets including the intermuscular membrane keep muscle bellies in place. We compared horizontal-rectus-muscle positions in up- and down-gaze using frontal CTs through the posterior pole of the eye. The bellies stayed in place while, anteriorly, the tendons bent up- and downward. We also found that the paths of horizontal rectus muscles were curved outwards in horizontal CTs. We surmised that retrobulbar pressure in the fat, resulting from four rectus muscles pulling the eyeball into the orbit, is contained by rectus muscles and connective-tissue sheets and that the resulting tension in the sheets keeps the muscles in place. Years later we repeated the CT study in a Crouzon patient whose bony orbital rim was displaced 2cm posteriorly, preventing pulley-band fixation to the bone: No vertical shift of horizontal rectus muscle bellies occurred in up- and down-gaze. Finally, we developed a mathematical finite-element model of orbit, muscles, fat and eyeball to study whether fat with enveloping connective-tissue sheets could keep eye muscles in place. In simulated eye movements, the retrobulbar fat, with low elasticity as found in vivo, not only kept the eyeball in place but also horizontal rectus muscle bellies in up- and down-gaze and vertical recti in left- and right-gaze.

KEYWORDS
Active pulley hypothesis; check ligament; extraocular muscle pulley; eye muscle; Helmholtz’s half-angle rule; Listings’ law; retrobullar fat; soft-tissue finite-element model

The recent review by Joel Miller[1] of Extraocular Muscle Pulleys with a critical appraisal of (i) the Pulley Concept of Miller and Demer,[2] (ii) the Active Pulley Hypothesis by Demer[3] and (iii) the Extraocular Muscle Compartments Hypothesis by Demer[4] explains the subtle differences between these Pulley Hypotheses in great detail. The impression is raised that, notwithstanding the differences between Active and Passive Pulleys, all agree that eye muscles are kept in place by connective-tissue bands between the rectus muscles and the orbital wall, thereby exerting pulley action. In the review by Joel Miller[1], 63% of the references originate from the debating authors themselves, the review disregards alternative explanations for pulley action and makes it seem as if the history of pulleys began in 1989.

History of extraocular-muscle-pulley connective-tissue bands

Connective-tissue bands with a presumed pulley effect were first described by Jacques René Tenon in 1805. Tenon was a member of the Section for Anatomy and Zoology of the Académie de Sciences of the Institut de France in Paris and gave a lecture[5] for the Académie in 1805 about the connective tissue enveloping the eye. Tenon was a surgeon and studied fresh heads anatomically. He sawed the head in the median plane and in the frontal plane just posterior of the orbital apex and then prepared the orbit from posterior to anterior,[5] thereby identifying not only the capsule that now bears his name but also ”faisceaux tendineux” acting as a ”poulie de renvoi”: “This fascicle arises on the outside of the muscle, behind the tendon, after which it proceeds anteriorly and laterally, at an ever greater distance

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from the muscle, to the lateral corner of the orbit, where it attaches to the bone very near the lower edge of the lacrimal gland. Due to this position, the fascia forces the tendon of the abductor to bend; by changing its direction in this way, it plays the role of a pulley in relation to the tendon and the entire muscle."[5]

The fascia and its presumed pulley action were described again by the early strabismus surgeons Amédée Bonnet[6] in Lyon and Joseph Michael Ferrall[7] in Dublin, both in 1841. In 1888, Philibert Constant Sappey, professor of anatomy and president of the Académie Nationale de Médecine in Paris, described the connective-tissue pulley bands and their smooth-muscle fibers in his four-volume textbook of anatomy:[8] "Second-order expansions, or tendinous slips. … That of the lateral rectus muscle sheath is the strongest of all. It runs outwards and forwards, attaching itself to the lateral orbital wall, 2 mm behind and slightly above the lateral palpebral ligament. At its origin, the ligament is continuous with the fibrous muscle sheath, not at all with the muscle itself as Tenon thought and a number of authors after him. During this first part of its pathway, it is exclusively and constantly fibrous; in the second part, i.e. at the level of its fixed insertion, it is made up of bands of smooth muscle fibers, these forming a true muscle, which I shall name the lateral orbital muscle. This expansion serves the following purposes: first, to support the lateral rectus as it winds round the eyeball following contraction of the opposing muscle, and to prevent any compression this muscle might exert on the eye, secondly, to restrict its shortening. It represents, in other words, a pulley ('poulie de renvoi') and a check ligament ('tendon d' arrèt')."[8]

Bellies of horizontal rectus muscles do not shift vertically in up- or downgaze

Anatomical structures that stabilize the rectus muscles in their retrobulbar path became important when David Robinson's strabismus model[9] predicted unnatural eye motility in eccentric gaze. His model assumed that an eye muscle followed the (almost) shortest path from origin to insertion. In upgaze, for instance, this caused the horizontal rectus muscles to shift upward so much that they became elevators: the "bridle effect."

In 1984, to check the prediction of Robinson's model, our research group in Amsterdam compared horizontal-rectus-muscle positions in up-gaze with those in down-gaze using frontal CTs through the posterior pole of the eye.[10,11] The rectus muscle bellies stayed in place while, anteriorly, their tendons bent up- and downward. Something held the muscle bellies in place, what was it?

In horizontal CTs of the eye in primary position, the paths of the horizontal rectus muscles were curved outwards. This, we thought, indicated retrobulbar pressure that is inevitably built up by the four rectus muscles pulling the eyeball into the orbit. The pressure in the retrobulbar fat is contained by the rectus muscles that are, hence, pressed outward and by connective-tissue sheets enveloping retrobulbar fat, including the intermuscular membrane. We reasoned that the resulting tension in the connective-tissue sheets including the intermuscular membrane could keep the muscle bellies in place, explaining our first finding.

Koornneef[12] had described these membranes as "connective-tissue septa" and not as "intermuscular membrane," as only the part of the intermuscular membrane between superior and lateral rectus could clearly be identified in his anatomical sections. But the existence of the intermuscular membrane in other quadrants is evident: When ophthalmologists give a retrobulbar injection between the lateral and inferior rectus muscles, they feel a clear resistance before the needle enters the retrobulbar space, caused by the membrane's sturdy texture.

Direction of pull that an eye muscle exerts on the eyeball in eye movements out of the muscle plane

In 1986, Gerold Kolling, Bob van Dijk and I studied different coordinate systems,[13] including a new one compliant with von Helmholtz's half-angle rule,[14] to describe strabismus angles in superior oblique muscle palsy and surgery. For the analysis of hypertropia and excyclotropia in ad- and abduction, we asked ourselves: What is the direction of pull that an eye muscle exerts on the eyeball in eye movements out of the plane of the muscle?[15] As Kolling had just finished his Habilitationsschrift[16] (second PhD thesis) summarizing the results of 200 oblique muscle operations, we analyzed strabismus angles in oblique muscle palsy and the results of oblique muscle surgery. We were especially interested in the differences in vertical deviation and in excyclotropia in ab- as compared to adduction. With my version of Robinson's model,[17,18] we studied the influence of different directions of pull, either rotating with the muscle out of the plane of the muscle or constant in the orbital frame, on vertical deviation and on excyclotropia in ad- as compared to abduction.[15]

Miller and Robins[19] had found, in a study in monkeys in 1987 using radiopaque markers and X-rays, that "the point of tangency of the lateral rectus with the globe – and so the muscle plane – to remain approximately fixed relative to the orbit" and then concluded that the effective direction of pull of the muscle, "the unit moment vector m is approximately fixed as well." When personally commenting on a draft of Miller's subsequent paper[2] in the autumn of 1987, I pointed out that that depended on the source of the force that keeps the muscle belly in place and, hence, keeps the muscle bent. I reasoned that the effective direction of pull rotates out of the plane of the muscle when this force is delivered by connective-tissue sheets enveloping the retrobulbar fat like the intermuscular membrane and the orbital wall.[15] It remains fixed in the orbital frame when this force is delivered by Tenon's capsule and the eye.[15] (Note that halfway in between the two is compliant with Listings' Law.[20]) Miller then described the pulley concept.[2]

What keeps the horizontal rectus muscle belly in place in up- and downgaze ?

Perimuscular tissues keep the rectus muscle belly in place at the level of the posterior pole of the eye, thereby exerting pulley action. Which tissues keep the muscle belly in place is subject to debate, however. Let us consider the horizontal rectus muscles that do not shift vertically in up- or downgaze, which would occur when the muscles took the shortest path from origin to insertion.

In Tenon's pulley concept,[5] in Sappey's pulley concept,[8] in the Pulley Concept of Miller and Demer[2] and in the Active Pulley Hypothesis,[3] vertical shift of horizontal rectus muscles in up- and downgaze is limited by a connective-tissue band with smooth-muscle cells and elastin fibers between the medial rectus muscle and the medial bony orbital rim and, similarly, between the lateral rectus muscle and the lateral bony orbital rim.

These concepts are questionable, however, because the band's attachment to the rectus muscle moves from 10 mm anterior to 10 mm posterior when the eye looks from 50° left to 50° right. It is hard to image that a horizontally mounted band that permits 20 mm of sagittal movement could restrain the eye muscle vertically.

To both stabilize the muscle and permit large horizontal eye movements, the connective-tissue band would have to be very elastic. To examine its elasticity we measured the relation between force and length of the connective-tissue band between the medial canthus and the medial rectus, 5 min after orbital exenteration.[21] We found that the band was slack but, when extended, very stiff, a mechanical behavior similar to what we found in eye muscles with a long-standing palsy, in force-length measurements during strabismus surgery in local, eye-drop anesthesia.[22] The connective-tissue band certainly did not possess the elasticity needed to restrain vertical shift of the medial rectus muscle while permitting large horizontal eye movements at the same time. The fact that smooth muscle in the connective-tissue band had not been innervated for a few minutes does not distract from this argument as the band should still have been elastic, unlike what we found.

The proximal end of the connective-tissue band is attached to the bony orbital rim. Does vertical shift of horizontal-rectus-muscle bellies occur when the bony orbital rim is displaced and the attachment of the connective-tissue band to the bone cannot function as a pulley? We made CT-scans in a frontal plane through the posterior poles of the eyes of a patient with Crouzon syndrome,[21] who had orbits so shallow that the aperture of the bony orbit was situated at the level of the posterior pole. No vertical shift of horizontal rectus muscle bellies occurred when the patient looked up or down, and no horizontal shift of vertical rectus muscle bellies occurred when the patient looked left or right.[21] These findings in a patient with severe Crouzon syndrome strengthen the view we expressed in 1984[10,11] that the retrobulbar fat and its enveloping connective-tissue sheets, including the intermuscular membrane, alone are capable to limit sideways shift of rectus muscle bellies in eye movements out of the plane of the muscle, which would occur when the muscles took the shortest path from origin to insertion.

The Pulley Concept of Miller and Demer,[2] i.e. the Passive Pulley hypothesis,[23] proposes that the extraocular muscles can "slide freely through their sleeves,"[23] through a "pulley ring" of connective tissue at the proximal end of the connective-tissue band. However, strabismus surgeons who perform myopexies of the medial rectus muscle know that the white tissue around the muscle where the muscle perforates Tenon's capsule is firmly adherent to the muscle, and considerable force is needed to push back this tissue to expose the muscle and make room to put the suture through the muscle, 12–15 mm behind the insertion.

Four anatomical studies reject the proposal of sliding of the muscle through a pulley ring. Ruskell et al. found a narrow interval separating the muscles from the surrounding connective tissue in some preparations, consistent with a capacity to slide, but the tissues were contiguous in others.[24] They concluded that the structural organization of sleeves and their tendons, together with other presented factors, was inconsistent with a facility for the separate adjustment of sleeve position.

Felder et al. concluded that adhesions between pulley structure and the global layer argue against the ability to translate the pulley freely in an anterior-posterior axis.[25]

McClung et al. described a collagenous bridge between the distal third of the muscle and the orbital periosteum, attaching to the muscle by investing itself around orbital muscle fibers whereas, at the point of attachment, those fibers remain aligned with the remainder of the muscle, constituting a tubelike sheath with the reflected bulbar fascia on the global side of the muscle.[26] They interpreted this as the check ligament described by anatomists before.

The Active Pulley Hypothesis[3] proposes that the orbital and global layers of the eye muscles move independently of each other, and that the orbital layer inserts on and moves the sliding pulley ring.

However, McLoon et al. found significant interconnectedness of the connective-tissue elements with all the muscle fibers along the whole length of the muscle, including direct connection into the epimysium, strongly suggesting that individual isolated movements of compartments within the EOM are unlikely.[27]

Fat with enveloping connective-tissue sheets keeps the muscle belly in place

The pulley effect has been analyzed by Miller with a model of eye motility that has three degrees of freedom.[1,2] The model eyeball rotates about its center that is assumed to be fixed in the orbit. That was the case in David Robinson's model,[9] in Miller's version of the model[28] and in my version of the model.[17,18] Translation of the eye, i.e. movement of the eyeball in its entirety, is not possible in these models, and how the center of the eyeball is kept in place is not accounted for. In Miller's latest version,[29] translation of the model eyeball is possible, but the eyeball is not kept in place by rolling on the retrobulbar fat as in real life. In these models with three degrees of freedom, only pull of muscles and pull of connective-tissue bands are considered, but the pressure exerted by retrobulbar fat as reactive force to maintain the position of the eyeball is ignored. Models with three degrees of freedom with a fixed center of rotation that do not account for reactive forces are misleading for analysis of the suspension of the eyeball in the orbit. The retrobulbar fat is essential as a bearing for the rotating eye. If the retrobulbar fat was missing, the eyeball would be pulled into the orbit by the four rectus muscles. The eyeball rolls on the retrobulbar fat like in a ball joint. Therefore, the suspension of the eyeball in the orbit should be analyzed with finite-element models that allow six degrees of freedom, i.e. rotation of the eye and translation of the eye, both in three directions. To analyze whether the retrobulbar fat with its enveloping connective-tissue membranes can keep the rectus muscle bellies in place, we constructed a soft-tissue finite-element model.

Finite-element models are commonly used in engineering design, but they are also increasingly used to model soft bio-tissues. It was my privilege to collaborate with brilliant engineers from the Technical University Delft who were able to make such a complex model.[30] This soft-tissue, finite-element model takes all orbital tissues into account: not only the eye muscles and connective-tissue bands but also the bone and the retrobulbar fat. The anatomical representations of the eye, its muscles, the fat and the orbit, were mathematically divided into ten thousands of small elements, tetraeders. Material properties like elasticity were assigned to each element. The retrobulbar fat and its enveloping connective tissue sheets were considered as one material. The resulting 3D structure could be mathematically subjected to a force, generated, for instance, by a contracting muscle, or to a pressure or to any other intervention, even like a simulated orbital floor fracture. The resulting movement, rotation and deformation of the eye, its muscles and the fat were then calculated and displayed.

With this model, we tested our 1984 proposal[10,11] that the retrobulbar fat and its enveloping connective-tissue sheets, limit sideways shift of rectus muscle bellies in eye movements out of the plane of the muscle. We found that the retrobulbar fat and its enveloping connective-tissue sheets are well capable of keeping the rectus muscle bellies in place.[30] The retrobulbar fat has a very low elasticity – during orbital surgery, it behaves almost like a fluid – and one might think that the rectus muscles could shift sideways easily through the fat. We had found that the elasticity of retrobulbar fat in monkeys was between 300 Pa and 500 Pa,[31] more than 10 times lower than the elasticity of kidney fat of the same animals. Nevertheless, even when the retrobulbar fat and its enveloping connective-tissue sheets were assigned such a low elasticity in the finite-element model, the retrobulbar fat not only kept the eyeball in place but also kept the rectus muscle bellies in place when the eye rotated out of the plane of the muscle[30]: The bellies of the horizontal rectus muscles did not shift vertically in up- or downgaze, and the bellies of the vertical rectus muscles did not shift horizontally in left- or right-gaze, which would occur when the muscles took the shortest path from origin to insertion. This finding strengthens our proposal that it is the retrobulbar fat and its enveloping connective-tissue sheets, including the intermuscular membrane, which prevent sideways shift of rectus muscle bellies in eye movements out of the plane of the muscle[11] and thereby redirect muscle force.[15]

Until now, no other soft-tissue, finite-element model of the orbit, the eyeball, the eye muscles and the orbital fat have been reported. Such models, more elaborate than what the Technical University Delft made already, are urgently needed to provide detailed insight into the suspension of the eyeball and the eye muscles in the orbit.

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