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Reply

Reply to the Letter to Editor by J.L. Demer regarding: Van den Bedem, Schutte, van der Helm, and Simonsz: Mechanical properties and functional importance of pulley bands or '*Faisseaux Tendineux*' (Vision Research 45: 2710–2714, 2005)

Dear Editor,

We appreciate the careful analysis Demer has provided of our recent paper describing the first measurements of the mechanical properties of pulley bands. We wish to initially delineate the areas of agreement, before responding to the criticism of Demer in detail.

The extraocular muscle (EOM) bellies do not displace sideways in eye movements out of the plane of the muscle (Miller, 1989; Simonsz, Härting, deWaal, & Verbeeten, 1985). According to the Active Pulley Hypothesis (APH) (Demer, 2002; Demer, Oh, & Poukens, 2000; Kono, Clark, & Demer, 2002), this is accomplished by pulleys. The APH proposes rectus pulleys that consist of encircling collagen rings, stiffened by elastin and smooth muscle. These pulley rings are suspended anteriorly from the orbital rim by bands or 'slings' that mainly consist of collagen. In our original article, we have called these bands 'pulley bands'. In the APH, these bands are portrayed as springs (Demer et al., 2000, Fig. 10). The APH proposes that shifts of the pulley locations are generated by contractile activity of the orbital layers of EOMs acting against pulley band elasticity.

Existence of the pulley bands has been beyond dispute for almost two centuries (Tenon, 1816). However, opinions divide on whether stabilization of the EOM bellies is assigned, in part, to the pulleys and pulley bands. The EOM bellies can be kept in place by external forces on the muscles: via connections to the orbital wall, to the globe, to other muscles (via the intermuscular membrane) (Simonsz et al., 1985), by the supportive action of the fat (Schutte, van den Bedem, van Keulen, van der Helm, & Simonsz, 2006) and by bending stiffness of the muscles themselves.

Demer's criticism focuses primarily on the quality of the force–length measurements of the pulley bands, and on the question of what kept the muscle bellies in place in our patient with the extremely shallow orbits, due to Crouzon's syndrome.

We agree with Demer that the measurements were done with limited accuracy and that it was not easy to mark the anterior border of the cut-off periorbit at the point where the pulley band originated from the orbit. On the other hand, our measurements of the mechanical properties of these bands are the only measurements to date, and were performed on human specimens that were removed from the body five minutes prior to testing. Despite the fact that our study was exploratory in nature, the finding that the pulley bands have leash-like properties makes it difficult to conceive that the pulley bands play an important role in stabilizing EOM bellies.

The many studies by Demer and co-workers on pulleys, pulley bands and the APH, have not been supported by measurements of their mechanical properties. It is not possible to derive mechanical properties from MR images or histological sections.

What mechanical properties are required for a pulley band to keep an EOM bell in place? To stabilize a muscle belly, it should exert sufficient force on the muscle in the proper direction and, at the same time, it should be able to elongate sufficiently to allow for large eye rotations. However, after elongation of the pulley band, we found it to be stiff, like a leash. As such, it seemed unsuited to keep a muscle in place. We list the following two arguments:

1. *The mechanical properties of the pulley bands do not allow for gradual force increase as needed to stabilize the EOM bellies*. The force–length relationship of a passive structure has a zero length below which no force is present, a stiffness that determines the force as a result of the lengthening above the zero length, and a maximal strain. Most ligaments in the human body have a maximal strain of about 5–7%, meaning a maximal elongation of 0.5–0.7 mm when assuming a zero length of 10 mm of the pulley band. This is in agreement with our findings: we reported that the ligaments are almost immediately taut after stretching beyond their zero length. An elongation of 0.5–0.7 mm and a sudden increase of force is not compatible with the APH (Fig. 1), assuming that the attachment of the pulley band to the muscle is rigid. Only if the muscle could slide through the pulley ring this would be possible; the muscle would have to slide 18 mm back and forth when looking from far left to far right. This is not the case. McClung, Allman, Dimitrova, and Goldberg (2006) found in histological sections that the pulley bands are attached to the rectus muscles. In addition, in the specimens removed from the patients 5 min previously, we found that the whitish connective tissue surrounding

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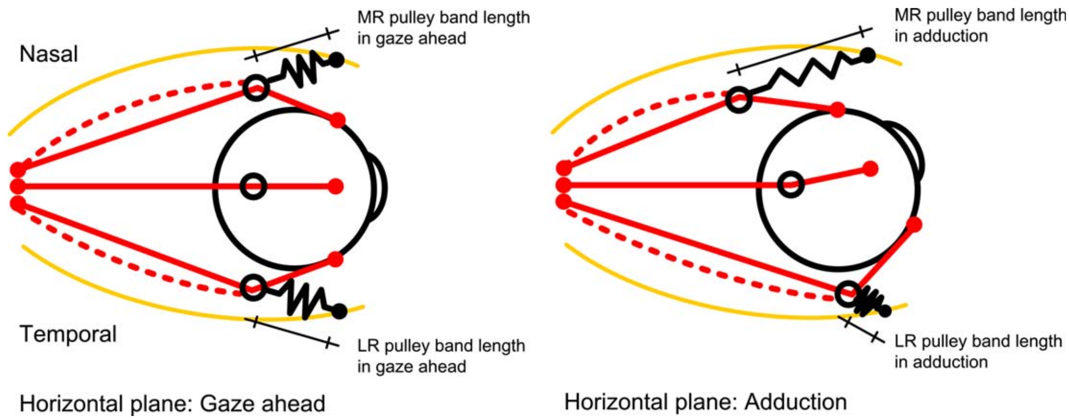

Fig. 1. This figure is redrawn from Demer et al. (2000). The right panel shows the shortening and lengthening of the lateral rectus (LR) and medial rectus (MR) pulley bands during adduction. The insertion of the pulley band on the muscle moves approximately 18 mm when looking from far left to far right. Alternatively, the muscle would have to slide 18 mm through the pulley ring.

the muscle, which represents the pulley ring, was tightly adherent to the muscle (van den Bedem, Schutte, van der Helm, & Simonsz, 2005).

2. *The line of action of the pulley bands is not suited to stabilize the EOM bellies.* If a medial rectus muscle belly would not be stabilized, the muscle would shift up- and downward in vertical gaze shifts because the muscle would take the shortest path over the globe (Robinson, 1975), a great circle. The *vertical* force needed to restrain this vertical movement can hardly be delivered by a structure in the *horizontal* plane.

Finally, the patient with the extreme Crouzon's syndrome had shallow orbits to the extent that the entrance of the orbit was at the level of the posterior pole of the eye. Demer states: "Even if parts of the globe were anterior to some orbital bones, the soft tissues and slightly more remote bones could stabilize the rectus pulleys." We think that stabilization of the muscle belly can be accomplished by external forces on the muscles: via connections to the globe, to other muscles via the intermuscular membrane (very thick in our patient), by the supportive action of the fat (Schutte et al., 2006) and by bending stiffness of the muscles themselves. Together, these managed to stabilize the inferior rectus muscle belly in our patient as is shown in video 4, made from below during surgery: the direction of the anterior part of the tendon of the inferior rectus muscle almost fully rotated with the eye when the patient looked from left to right.

We conclude that mechanical evidence for the active pulley hypothesis has been lacking. Other studies (Dimitrova, Shall, & Goldberg, 2003; McClung et al., 2006) have questioned the functional importance of the pulley bands. It is more likely that the pulley bands act as ligamentous constraints to prevent excessive eye rotation and, hence, prevent excessive stretching of the optic nerve.

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