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Re: Magnetic Resonance Imaging of the Globe–Tendon Interface for Extraocular Muscles: Is There an "Arc of Contact"?

EDITOR:

EACH EXTRAOCULAR MUSCLE NORMALLY LEAVES ITS INSERtion, wraps around the globe along a contact arc, and departs, tangent to the globe (perpendicular to its radius, departure angle = 0), at a departure point en route to its connective tissue pulley or trochlea. Recessed muscles, muscles with posterior sutures, and muscles in extreme ipsiversive gaze can unwrap from the globe, lose tangency (departure angle >0), and suffer their oculorotary force reduced by the cosine of the departure angle.

Clark and Demer[1] mean to cast doubt on the contact arc notion. Accordingly, they looked for departure angles >0, but only with eyes in extreme ipsiversive gaze where muscles were unwrapped from the globe and in abnormal and operated eyes—all cases for which contact arc models would also predict loss of tangency.[2] Their study therefore does not bear on the existence of contact arcs.

Instead of simply measuring departure angles relative to globe tangents, Clark and Demer[1] wrongly assert that contact arcs require muscles to take straight paths to their anatomic origins, as though pulleys did not exist, and compare their measurements to "predicted" departure angles, determined by globe center (their white pixel "1"), insertion ("2"), and anatomic origin ("4"). Their magnetic resonance imaging analysis is consequently spurious.

Looking away from these conceptual errors, one can ask how large the claimed effects were. The largest deviation from tangency reported for normal eyes is 6.2°. The cosine of 6.2° is 0.995, which means that the reduction in oculorotary torque related to a loss of tangency is 0.5%. Far from "fundamentally alter[ing] the globe–tendon interface," effects of this size would best be described as "negligible."

Nothing in their article in any way discredits existing modeling.

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REPLY

WE THANK DRS. MILLER AND SCOTT FOR REVIEWING OUR work and enabling us to elaborate. As they succinctly state, the "arc of contact" model predicts an extraocular muscle departure angle of 0°—a perfect tangent to the globe whereby all extraocular muscle force parallels globe circumference at the insertion. Given this defining prediction, any data that convincingly demonstrate a significantly nonzero departure angle under appropriate conditions is inconsistent with the "arc of contact" model. Any such inconsistency, if observed, should be interpreted within the context of 2 additional considerations. First, nonzero departure angles are predicted by the arc of contact model when globe rotations exceed an angle where tendon tangency is lost and the only tendon contact with the globe is at the scleral insertion. In other words, the arc of contact predicts a 0° departure angle only when at least some of the extraocular tendon remains wrapped around the globe. Second, a nonzero departure angle would only be problematic for the arc of contact theory were it sufficiently different from 0° to materially affect the mechanics of ocular rotation. We agree that a slightly nonzero departure angle, even if statistically significantly so, may have too small a mechanical effect for its existence to compromise the arc of contact model for practical purposes. We interpret the letter by Miller and Scott as arguing for the second consideration. We maintain that we have provided evidence that nonzero tendon departure angles are often too large to be neglected.

Contrary to the assertion of Miller and Scott, the measured ipsiversive globe rotations in normal subjects were not "extreme," but instead were well within the ±55° range of physiologic duction,[1] averaging between 22.6° adduction for the medial rectus to 27.6° abduction for the lateral rectus. For this range of ductions, our imaging data show that the wrap around condition was maintained for all muscles, with a predicted departure angle assuming an arc of contact of 0°, except for the inferior rectus, with a predicted departure angle of only 1.2°. The actual departure angles, however, significantly exceeded 0° for all muscles because the tendons were not infinitely thin. Despite wrapping around the globe for some distance posterior to their insertions, the tendon bulk produced a nonzero departure angle for all extraocular muscles, violating the fundamental premise of the arc of contact model.

In addition, while the maximum reduction in tangential (oculorotary) force created by observed nonzero departure angles was <7%, the nonzero departure angles for the healthy medial rectus, lateral rectus, and inferior rectus endow each muscle's force vector with a substantial component that is perpendicular to the globe surface and is therefore considered "normal" in the geometric sense, thereby acting only to translate the globe linearly. The largest departure angle measured in normal subjects was 16.0°, not 6.2°. Oculorotary force is proportional to the cosine of the departure angle, and therefore a 16° departure angle reduces oculorotary force by about 4%, not 0.5%. The translational force component, on the other hand, is proportional to the sine of the departure angle. An average 5° departure angle converts about 9% of medial rectus and lateral rectus contractile force from rotation into translation, likely accounting for the much larger medial shifts of the globe observed during adduction and lateral shifts during abduction[2] than the 0.1-mm mediolateral translation predicted by the Orbit 1.8 program.[3] Similarly, a 16° departure angle converts almost 28% of the inferior rectus force into inferior translational force. Forces of this magnitude are not "negligible" and should not be ignored in precise biomechanical modeling.

In our subjects with strabismus, the arc of contact model failed to accurately predict the oculorotary forces in abducens palsies after strabismus surgery. In particular, even for surgical resection, where the original insertion and therefore the "arc of contact" would have been presumed to be preserved under the traditional construct, the increased bulk of muscle tissue at the insertion diminishes oculorotary force and increases translational force—an effect discernable only when the angle at insertion is determined in vivo with imaging.

As for the imaging landmarks used for our magnetic resonance imaging analysis, the only important landmarks required to properly measure the departure angle of a rectus muscle from the globe are the globe's center, the muscle's insertion, and the immediate path of the muscle departing its insertion. Together, these measurements are not "spurious" but rather define the angle at insertion. The fourth landmark, the center of the posterior muscle belly, was not necessary for most subjects because the muscle's tendon posterior to its insertion was in contact with the sclera.

To summarize, our data show that the departure angles of extraocular tendons from the globe are sometimes significantly >0° and that these departure angles can be mechanically significant. When this is the case, models that rely upon the arc of contact may therefore not accurately predict of the mechanics of normal motility, strabismus, or strabismus surgery. We recognize that no mathematical model can ever be perfect, yet models can still be useful when their limitations are recognized. We suggest that models and concepts of extraocular muscle action that are heavily reliant on the concept of the arc of contact should be modified to include consideration of the actual muscle departure angles; otherwise, the mechanical predictions of such models should be interpreted with appropriate caution.

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