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REVIEW ARTICLE

Functional anatomy of the orbit in strabismus surgery: Connective tissues, pulleys, and the modern surgical implications of the "arc of contact" paradigm

Paulo Freitas-da-Costa[1,2,3] | **Maria Dulce Madeira**[3,4]

[1]Department of Ophthalmology, São João University Hospital Center, Porto, Portugal
[2]Department of Surgery and Physiology, Faculty of Medicine, University of Porto, Porto, Portugal
[3]Anatomy Unit, Department of Biomedicine, Faculty of Medicine, University of Porto, Porto, Portugal
[4]Center for Health Technology and Services Research (CINTESIS), Porto, Portugal

Correspondence
Paulo Freitas-da-Costa, Anatomy Unit, Department of Biomedicine, Faculty of Medicine, University of Porto, Alameda Prof. Hernâni Monteiro, 4200-319 Porto, Portugal.
Email: paulofreitascosta@gmail.com

Abstract

Oculomotricity is a multidimensional domain characterised by a delicate interplay of anatomical structures and physiological processes. This manuscript meticulously dissects the nuances of this interplay, bringing to the fore the integral role of the extraocular muscles (EOMs) and their intricate relationship with the myriad orbital connective tissues as it harmoniously orchestrates binocular movements, ensuring synchronised and fluid visual tracking. Historically, the peripheral oculomotor apparatus was conceptualised as a rudimentary system predominantly driven by neural directives. While widely accepted, this perspective offered a limited view of the complexities inherent in ocular movement mechanics. The twentieth century heralded a paradigm shift in this understanding. With advances in anatomical research and imaging techniques, a much clearer picture of the gross anatomy of the EOMs emerged. This clarity challenged traditional viewpoints, suggesting that the inherent biomechanical properties of the EOMs, coupled with their associated tissue pulleys, play a pivotal role in dictating eye movement dynamics. Central to this revised understanding is the "arc of contact" paradigm. This concept delves deep into the mechanics of eye rotation, elucidating the significance of the point of contact between the EOMs and the eyeball. The arc of contact is not just a static anatomical feature; its length and orientation play a crucial role in determining the effective torque generated by a muscle, thereby influencing the amplitude and direction of eye rotation. The dynamic nature of this arc, influenced by the position and tension of the muscle pulleys, offers a more comprehensive model for understanding ocular kinematics. Previously overlooked in traditional models, muscle pulleys have now emerged as central players in the biomechanics of eye movement. These anatomical structures, formed by dense connective tissues, guide the paths of the EOMs, ensuring that their pulling angles remain optimal across a range of gaze directions. The non-linear paths resulting from these pulleys provide a more dynamic and intricate understanding of eye movement, challenging two-dimensional, linear models of orbital anatomy. The implications of these revelations extend beyond mere theoretical knowledge. The insights garnered from this research promise transformative potential in the realm of strabismus surgery. Recognising the pivotal role of muscle pulleys and the "arc of contact" paradigm allows for more precise surgical interventions, ensuring better post-operative outcomes and minimising the risk of complications. Surgical procedures that previously relied on basic mechanical principles now stand to benefit from a more nuanced understanding of the underlying anatomical and physiological dynamics. In conclusion, this manuscript serves as a testament to the ever-evolving nature of scientific knowledge. Challenging established norms and introducing fresh perspectives pave the way for more effective and informed clinical interventions in strabismus surgery.

KEYWORDS
anatomy, connective tissue, eye movements, oculomotor muscles, orbit, rectus muscle pulleys, regional, strabismus

1 | THE ANATOMICAL AND PHYSIOLOGICAL BASIS OF EYE MOVEMENTS AND STRABISMUS

Understanding abnormal eye movement or oculomotricity can often be intricate, demanding a thorough grasp of the anatomy of the extraocular muscles (EOMs), the complex web of orbital connective tissues, and the foundational principles of motor innervation that harmoniously dictate binocular movements. What might come as unexpected is the notable clarity we have achieved regarding the basic gross anatomy of the EOMs towards the close of the twentieth century. The peripheral oculomotor apparatus was traditionally perceived as a rudimentary system, performing intricate activities directed solely by neural commands. However, a rivalling perspective has emerged, postulating that many essential facets of eye movement owe their origin to the inherent properties of the EOMs and their connected tissue pulleys.

1.1 | Gross anatomy of the extraocular muscles

The historically understood six EOMs are the effector arm of the ocular motor system (Lambert & Lyons, 2017; Standring, 2021; Taylor & Hoyt, 2005; Von Noorden & Campos, 2002; Yanoff & Duker, 2014). The path of the extraocular muscles from their origin to their insertion determines their effects on eye movement, and a thorough knowledge of the relationship of the muscles with each other as they course to their insertions is requisite for successful orbital and strabismus surgery.

Five of the six EOMs originate at the orbital apex. The superior, inferior, medial, and lateral rectus muscles arise from the annulus of Zinn, an oval, fibrous ring at the orbital apex. The superior oblique muscle arises from the periorbita of the superonasal orbital wall just above the annulus of Zinn. The sixth EOM, the inferior oblique, originates from the maxillary bone adjacent to the lacrimal fossa, posterior to the orbital rim (Standring, 2021).

These EOMs are highly specialised, and each EOM consists of two kinds of compartments (Demer, 2015). The global layer (GL) controls oculorotary tension, while the orbital layer (OL) controls the pulling direction by regulating the position of the connective tissue pulleys. The GL and OL contain fibre types with different metabolic and structural properties (Lim et al., 2007; Oh et al., 2001). A second kind of compartmentalisation divides each GL transversely according to specialised motor nerve intramuscular arborisation of approximately equal proportion, enabling differential contraction (da Silva Costa et al., 2011; Demer, 2015). Notably, longitudinal splitting of the lateral rectus muscle is a characteristic observed in various congenital cranial dysinnervation disorders (Demer et al., 2005; Okanobu et al., 2009). Furthermore, the abducens nerve frequently splits into two or more distinct branches (Ozveren et al., 2003; Zhang et al., 2012), occasionally exhibiting a notable separation at the level of the cavernous sinus (Zhang et al., 2012). Similarly, the medial rectus motor nerve divides into superior and inferior branches (da Silva Costa et al., 2011). The superior and inferior obliques and the inferior rectus muscles also receive innervation in a compartmentalised manner. However, this selective compartmental innervation seems conspicuously absent in the superior rectus muscle (da Silva Costa et al., 2011; Demer, 2015; Le et al., 2015).

The rectus EOMs course anteriorly through the orbital fat until they enter their connective tissue pulleys that ensheath them as they penetrate posterior Tenon's fascia (Figure 1). Contrary to what is described, there is no "muscle cone" of connective tissue among the adjacent rectus EOM bellies in the mid-to-deep orbit (Figure 1; Simonsz, 2020). The rectus muscles insert into the sclera anteriorly to the globe's equator. The medial rectus inserts closest to the limbus, followed by the inferior, lateral, and superior recti in that order. The spatial formation created by connecting their insertion is called the spiral of Tillaux. The insertion line of the superior and inferior recti migrates posteriorly from the nasal to the temporal edge of the tendon. The sclera is thinnest (approximately 0.3 mm thick) just posterior to the rectus insertions (Standring, 2021; Yanoff & Duker, 2014).

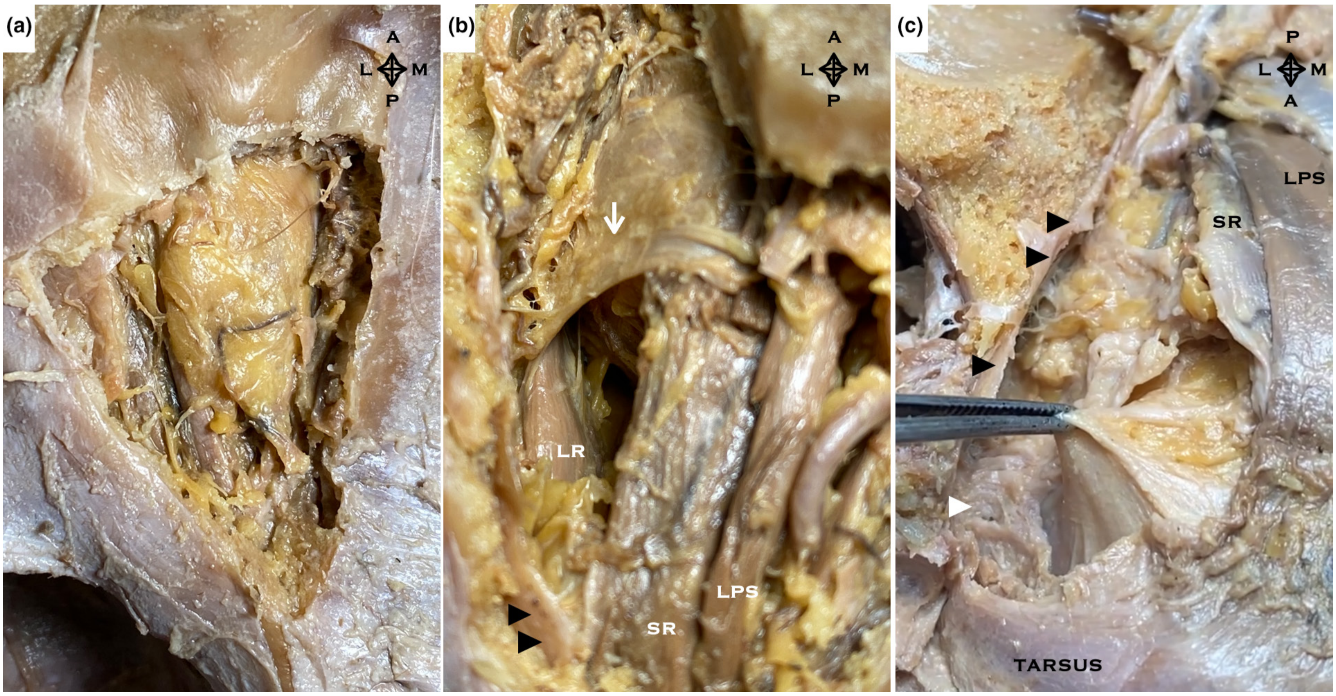

FIGURE 1 Anatomical dissection of an orbit of a formalin-fixed cadaver in a superior approach. The extraconal adipose tissue was removed. (a, b) left orbit, same dissection, different steps, superior aspect. (a) After periorbita opening. Adipose tissue forms the filling of the muscular cone in the mid-to-deep orbit. (b) The intraconal adipose was removed, and the LR-SR/LPS band (white arrow) of connective tissue in the anterior orbit was exposed. (c) Right orbit, superior aspect. After opening and excising the LR-SR/LPS band, the Tenon's capsule is exposed and pulled here with forceps. A, anterior; Black arrowhead, periorbita; Black star, residual lacrimal gland tissue; P, posterior; L, lateral; LPS levator palpebrae superioris; LR lateral rectus; M, medial; SR superior rectus; White arrowhead, lateral check ligament or lateral capsulopalpebral fascia.

The superior oblique muscle remains tethered to the periorbita via connective tissues as it courses anteriorly and then narrows to become continuous with its long, slender tendon. The two layers of the superior oblique muscle have a distinct arrangement: the concentric OL terminates proximally to the trochlea on a sheath located on the periphery, whereas the GL ends on the tendon fibres that run parallel, similar to those of the rectus muscles. However, these fibres are uniquely coiled into a cylindrical shape as they pass through the trochlea, the rigid, cartilaginous pulley on the orbit's superonasal wall. (Figure 2a). After reflection in the trochlea, the tendon passes beneath the superior rectus, thins and flattens as it spreads to its broad scleral insertion posterolaterally on the globe while the sheath inserts on the SR pulley (Figure 2b). The tendon insertion is functionally separated into two parts, the anterior one-third and the posterior two-thirds. The anterior one-third of the tendon functions almost exclusively to incycloduct the globe. The posterior two-thirds of the tendon functions to depress and abduct the globe (Rosenbaum & Santiago, 1999; Von Noorden & Campos, 2002).

The inferior oblique muscle originates from the inferonasal orbital rim (Figure 2c) and runs laterally to enter its connective tissue pulley immediately inferior to the inferior rectus at the point it penetrates Tenon's fascia. The inferior oblique muscle inserts into the posterior inferolateral sclera (Figure 2d). The insertion lies close to the macula and the inferotemporal vortex vein.

The axes of the bony orbits are angled about 23° laterally from the midsagittal plane (Figure 3). The array of the rectus EOMs and the superior oblique is conical. As they continue anteriorly, the rectus EOMs thin to become strap-like bands about 10 mm in width, and ultimately, their GLs become continuous with tendons that insert on the globe (Lambert & Lyons, 2017; Standring, 2021). The superior oblique would do the same, except its tendon rolls up within the trochlea and then unrolls distally.

1.2 | Basic mechanics and the dynamics of eye movements: An insight into kinematics

The eye movements, as mechanical events, are subject to the general laws of kinematics. While delving deep into the intricacies of kinematics is optional for comprehending the clinical nuances of eye movements, some foundational concepts must be discussed.

Consider a spheroid body freely hanging in space. Every conceivable motion of this body can be broken down into one or more of six fundamental movements (Von Noorden & Campos, 2002). Three of these are translatory:

1. Lateral movement (side-to-side)
2. Vertical movement (up and down)
3. Anteroposterior movement (forward-and-backward)

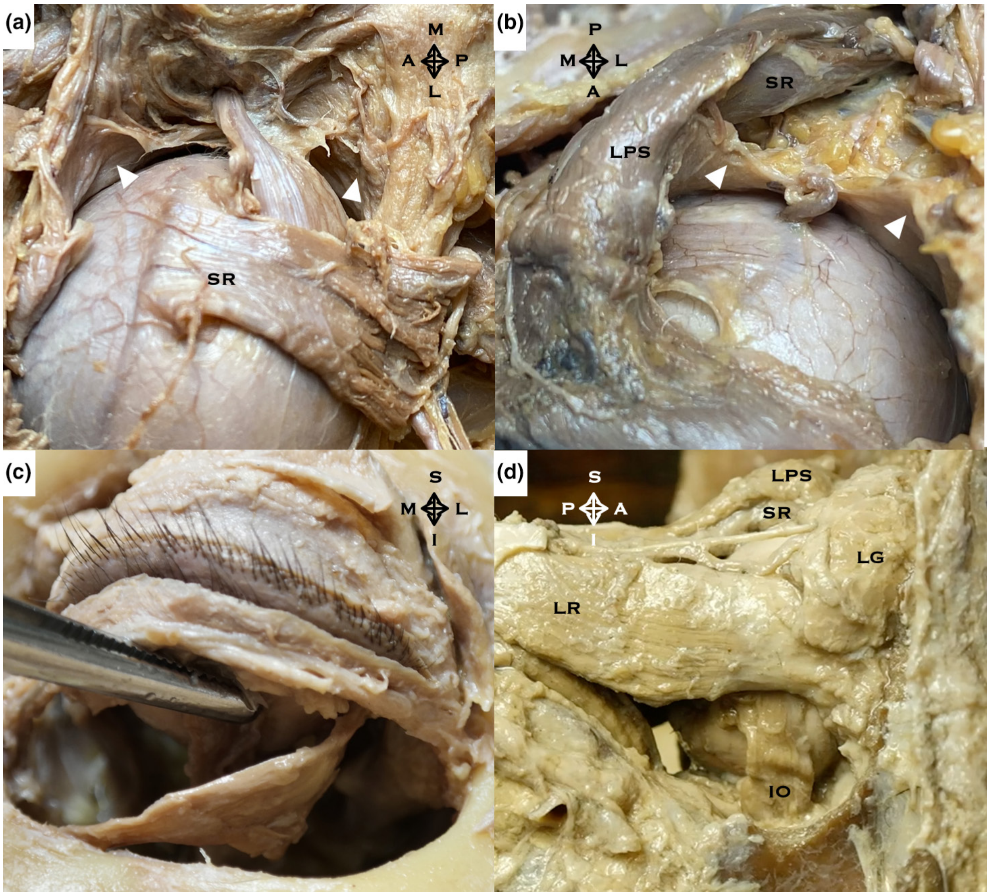

FIGURE 2 Orbital anatomical dissection in different formalin-fixed cadavers. Exposure after muscle individualisation, cleaning and careful dissection of all surrounding connective and adipose tissue. (a) Left orbit, superolateral aspect. The superior oblique tendon rolls into a cylinder as it transits the trochlea; (b) Left orbit, anterosuperior aspect. Insertion of the superior oblique muscle tendon into the superolateral aspect of the globe after opening and dissection of Tenon's capsule (white arrowheads); (c) Left orbit, anterior aspect. Inferior oblique muscle origin and trajectory; (d) Right orbit, lateral aspect. Insertion of the inferior oblique (IO) muscle into the globe in the posterolateral and inferior quadrant. A, anterior; I, inferior; L, lateral; LG, lacrimal gland; LPS, levator palpebrae superioris; LR, lateral rectus; M, medial; P, posterior; S, superior; SR, superior rectus.

The other three movements are rotary, involving rotations around specific axes:

1. Vertical axis (yielding horizontal rotations)
2. Horizontal axis (yielding vertical rotations)
3. Anteroposterior axis (yielding torsional rotations)

When the spheroid body undergoes a translatory movement, its centre shifts with the motion. Contrastingly, the centre remains stationary during a pure rotation, exhibiting no motion or a zero-velocity state. This principle also applies to the human eye. When the eyeball undergoes rotation, it revolves around an internal point known as the centre of rotation. Historically, this centre was believed to be static. However, modern experiments contest this notion. Instead of remaining motionless during rotations, the eye's centre of rotation actually traces a semicircular path within the plane of rotation. This revelation implies that the mechanics of eye movements, even those that appear straightforward, harbour complexities. Yet, the translatory shifts in the eye's position can often be set aside for practical clinical purposes, focusing primarily on the rotations.

The eye, a nearly spherical organ, functions within a highly coordinated and systematic environment to facilitate movement. Understanding the eye's movements requires grasping its architecture and motility principles.

1.2.1 | Centre of rotation & degrees of freedom

The eyeball or globe rotates around a nearly fixed point, known as the centre of rotation. Consequently, while the eye has three axes (not six), it boasts only three degrees of freedom. It can revolve around:

- The anteroposterior or sagittal axis (y-axis), which aligns with the line of sight (Figure 2).
- The vertical axis (z-axis), perpendicular to the line of sight.

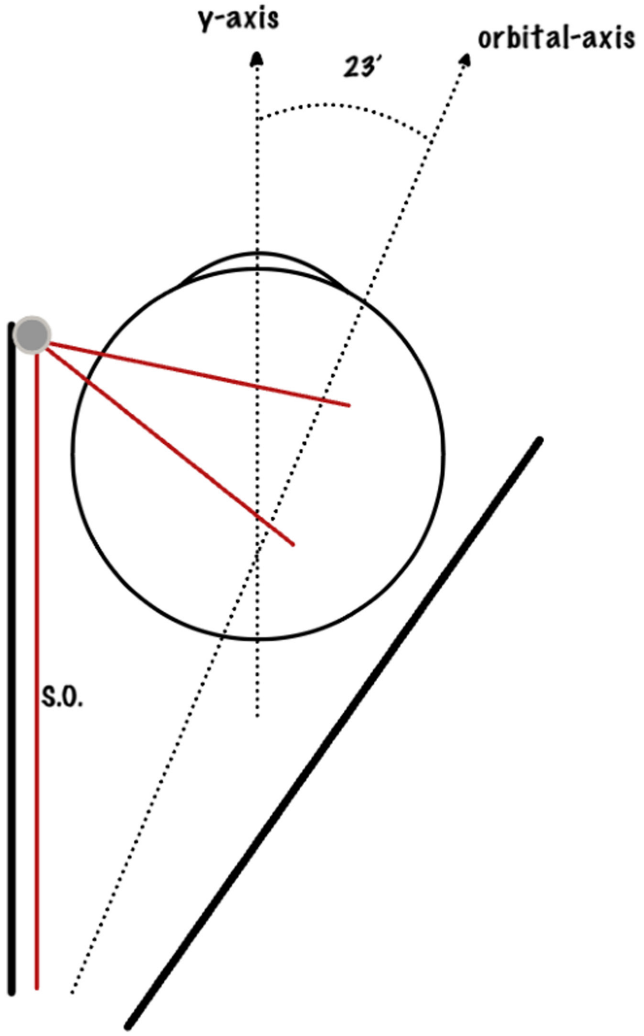

FIGURE 3 Relation of the orbital axis (equivalent to the superior rectus muscle plane) and the superior oblique muscle plane with the *y*-axis.

- The horizontal axis (*x*-axis) is also perpendicular to the line of sight.

These axes, mainly the vertical and horizontal, ideally lie within Listing's plane—a theoretical plane established within the orbit that intersects both the globe's equator and its centre of rotation when the eye is in its neutral or primary position (Von Noorden & Campos, 2002).

1.2.2 | Tangential point and arc of contact

The tangential point is where the muscle or its tendon makes its first contact with the eye. Drawing a tangent at this point provides insight into the muscle's pull direction. This point's position varies as the muscle contracts or relaxes and the globe rotates. Therefore, the *arc of contact*, the curve between the tangential point and the muscle's insertion centre on the sclera, fluctuates in length (Figure 4d). It elongates when the muscle is relaxed (and its opposite counterpart contracted) and contracts when it is taut (and its counterpart relaxed).

1.2.3 | Muscle plane and direction of pull

The muscle plane comprehensively explains how the muscle interacts with the globe. This plane is defined by two critical anatomical points: the muscle's origin and insertion point, along with the eye's centre of rotation. If we imagine an axis erected perpendicular to this muscle plane, right at the centre of rotation, it shall represent the direction in which the muscle exerts its primary force. Each muscle plane associated with different muscles will have its distinct axis of rotation perpendicular to that specific muscle plane, thereby indicating the primary direction of the muscle's action on the globe. (Von Noorden & Campos, 2002).

Traditionally, eye movement and the action of EOMs have been viewed through a relatively simple lens, leveraging basic mechanical principles. With advances in research, a more nuanced understanding of eye movement has emerged, shedding light on the complexities inherent in ocular kinematics. Historically, the efficiency with which a muscle can rotate the eyeball depended heavily on where the muscle attaches to the eye and the muscle's mass. The further forward from the centre the muscle attaches, and the greater its mass, the more effective its role in rotation. The medial rectus muscle exemplifies this principle perfectly, as it attaches nearer to the corneal limbus and is notably heavier than other muscles. The potential range of motion, or amplitude, that the eye can achieve due to a specific muscle's action is theoretically defined by how much the muscle can shorten. This potential shortening is, in turn, determined by the muscle's *arc of contact* with the eyeball. The longer this arc, the greater the muscle's shortening ability and potential to move the eye.

Our understanding of eye movement underwent a paradigm shift with the discovery of muscle pulleys, essential anatomical structures that play a crucial role in EOM function. Traditional concepts of eye movement, such as the arc of contact and muscle plane, were formulated based on two-dimensional, linear models of orbital anatomy. In light of the discovery of muscle pulleys, these models need reevaluation and reinterpretation. The non-linear paths resulting from these pulleys provide a more dynamic and intricate understanding of eye movement (Clark et al., 1999; Clark & Demer, 2018; Demer, 2003, 2004, 2006b; Demer et al., 1995, 2000; Miller, 1989, 2007).

1.3 | Orbital connective tissue apparatus anatomy

The orbital connective tissue structures provide more than passive eyeball support. These specialised fibrous systems play crucial roles

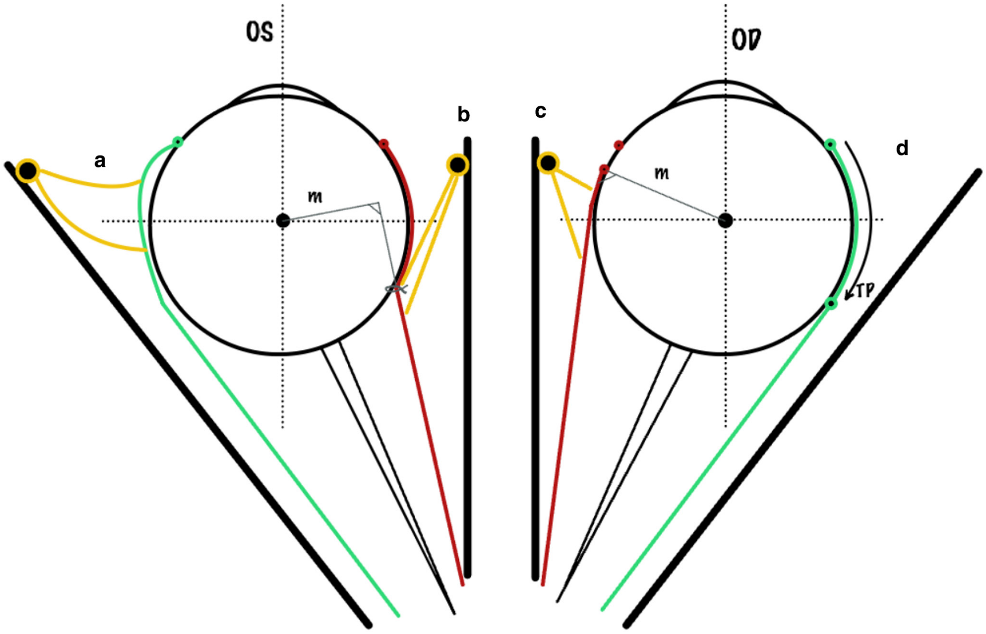

FIGURE 4 Orbit diagram. Representation of the pulley concept and its influence on the rectus muscles' non-linear path and their tendon's insertion angle. (a) Lateral rectus muscle with loss of tangency created by the pulley. (b) Posterior fixations suture of the medial rectus—the concept of cancelling the arc of contact with reduced lever arm length, compared to what happens in a recession (c). At the same time, there is a restriction in the longitudinal movement of the pulley with the inability of the tendon to telescope on it. (d) The traditional concept of a linear path of the lateral rectus muscle with the definition of the tangential point (TP) and arc of contact (curved arrow). OS left eye, OD right eye.

in maintaining the relative spatial relations of the ocular structures, aiding in eye movements, and ensuring that tension is appropriately distributed throughout the orbital content (Miller et al., 2003; Standring, 2021; Von Noorden & Campos, 2002).

1.3.1 | Stabilisation and spatial maintenance

Tenon's capsule (Figures 1, 5, and 6) acts as a fibrous exoskeleton for the eye. It surrounds the globe and provides a buffer against external forces, ensuring that the eye remains in orbit and maintains its structural integrity during rapid eye movements or external compressions.

1.3.2 | Facilitation of smooth eye movements

The muscle sheaths reflected from Tenon's capsule (Figure 5) provide a low-friction environment, allowing the extraocular muscles to contract and slide smoothly. This minimises resistance, ensuring rapid and precise eye movements.

1.3.3 | Anchoring and redirecting forces

The ligaments, particularly Whitnall's and Lockwood's ligaments, serve as robust anchorage points. They redirect the forces exerted by the eyelid's lifting mechanism and the actions of the inferior rectus and inferior oblique muscles, respectively. This ensures efficient translation of muscular contractions into specific eye movements. Two transverse laminae of connective tissue form Whitnall's ligament: the superior transverse ligament and the intermuscular transverse ligament. The superior transverse ligament thickens the sheath of the levator palpebrae superioris (LPS) muscle, extending laterally and medially to insert into the orbital walls just posterior to the superior orbital rim. The intermuscular transverse ligament is a dense sleeve situated between the SR and the distal portion of the LPS. Lockwood's ligament, a 5 to 8 mm wide thickening of Tenon's sleeves between the crossing points of the inferior rectus and inferior oblique muscles, extends laterally and medially. It becomes continuous with the medial and lateral recti pulley ring and, through them, to the orbital walls (Koornneef, 1977a, 1977b, 1977c, 1979). Additionally, its arcuate expansion to the orbit floor is crucial in explaining how an orbital floor fracture may limit vertical and horizontal eye movements.

1.3.4 | Limiting over-extension

The check ligaments, which span from the outer surfaces of the medial and lateral rectus muscles to the corresponding orbital wall, the posterior part of the palpebral ligament and conjunctival fornix (Kang et al., 2012; Ruskell et al., 2005), act to prevent overextension of these muscles (Figures 1c and 6f). This is particularly crucial

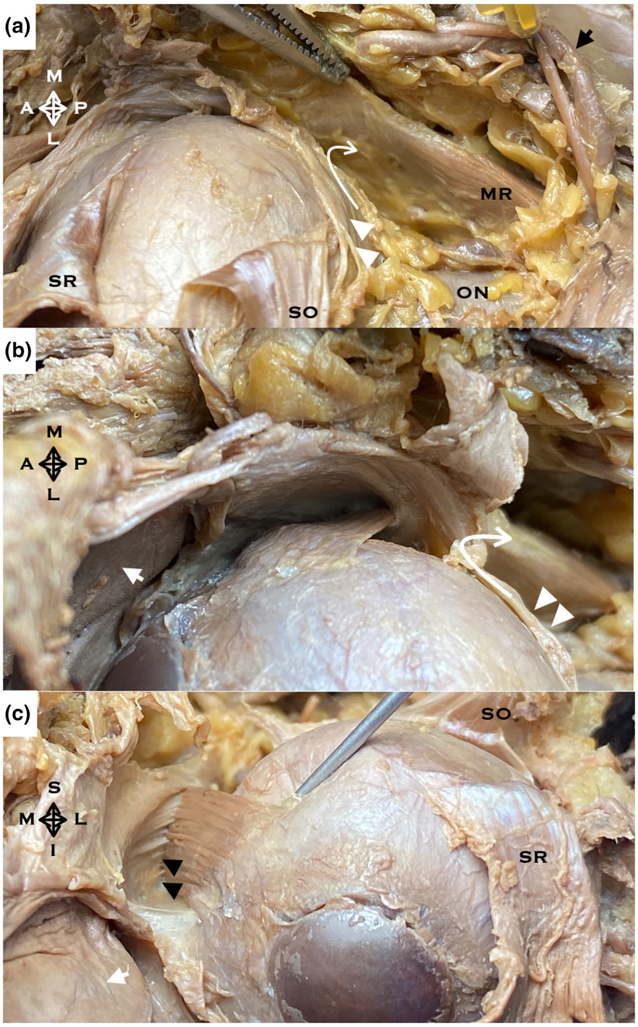

FIGURE 5 The right orbit of a formalin-fixed cadaver in a superior approach dissection. (a, b) Superior aspect. (c) Anterior aspect. The medial rectus muscle (MR) courses anteriorly through lobules of orbital fat until it enters the connective tissue pulley that ensheaths it as it penetrates posterior Tenon's fascia (*white arrowhead*). *Curved White Arrow*, the constitution of the muscular fascia by the reflection of the Tenon's capsule on the muscular belly; *Black arrowhead*, MR insertion on its pulley; White arrow, superior tarsus; *SR* superior rectus tendon anteriorly reflected, *SO* tendon of the superior oblique muscle reflected posterolaterally, *ON* optic nerve; *Black arrow*, ophthalmic artery and nasociliary nerve retracted with a needle. A, anterior; I, inferior; L, lateral; M, medial; P, posterior; S, superior.

during extreme gaze shifts or in the face of traumatic forces, ensuring that the muscles do not undergo damaging strain.

1.3.5 | Contribution to eyelid mechanics

The orbital connective tissue apparatus, especially Whitnall's transverse ligaments, plays an integral role in the dynamics of eyelid opening. It supports the LPS, transfers tension, and provides a pivot point, allowing for efficient eyelid elevation.

1.3.6 | Protection and integration

While these tissues support ocular mechanics, they also integrate the eyeball within the orbital structure, ensuring proper spacing between the globe and surrounding skeletal and soft tissue structures. They act as a protective barrier against external trauma, dispersing forces and minimising the risk of direct injury to the globe.

Koornneef's revolutionary observations on the intricacies of the orbital connective tissues have reshaped our understanding of ocular biomechanics. Recognising the wide-reaching effects of a localised “blowout” fracture, he postulated that the EOMs are interconnected in more intricate ways than previously believed. His meticulous studies on these tissues highlighted their uniformity across humans, indicating their potential evolutionary significance, particularly in their specific biomechanical functions (Koornneef, 1977c, 1979). Orbital histological studies have since expanded on Koornneef's findings. An established understanding of the connective tissue sleeves that envelope the rectus EOMs is now based. These sleeves provide a robust structural network near Tenon's capsule, just posterior to the globe equator (Figures 5 and 6). They form a cohesive bond with each other and the surrounding orbital walls (Demer et al., 1995). But what gives these sleeves their resilience? It is their unique composition of collagen and elastin, bolstered by the presence of smooth muscle (Clark et al., 1997; Demer, 2007; Demer et al., 1995, 1997, 2000; Koornneef, 1977c).

Furthermore, these findings have brought to light the existence of EOM pulleys. As vital constituents of the smooth muscle network, these pulleys form a 3D lattice (Demer, 2002; Miller et al., 2003). They are interconnected. The sleeves are coupled to the orbit walls by musculofribroelastic fibres and extend to adjacent rectus sleeves, forming bridges composed of dense connective and elastic tissue, acquiring a ring-shape band typically located close to the globe's equator (Figure 6; Demer et al., 1997; Miller et al., 2003). Notably, these connections also extend to both the medial and lateral portions of the tarsal plates (Figures 1c and 6f) – essential components of the upper and lower eyelids (Kakizaki et al., 2008; Kang et al., 2012; Ruskell et al., 2005).

Historically, Tenon's observations in 1805 brought attention to the orbital connective tissues (Tenon, 1806; Tenon et al., 2003). Later, the term “poulie,” which suggests a role in directing the path of the EOMs, was introduced by Sappey in the 19th century (Sappey, 1888). Despite these early insights, it took centuries before the significance of these structures was truly comprehended. The predominant belief favoured a simplified model, suggesting that the action of the EOMs was merely determined by their attachment points on the globe.

However, Miller highlighted the unlikely nature of this model, noting that the shortest path over the globe would require that the rectus EOMs side slips over the globe in gaze positions transverse to their paths (Miller, 1989). Thus, in an upward gaze, the medial and lateral rectus muscles would side slip superiorly, and in a lateral gaze, the vertical rectus muscles would side slip laterally. The geometrically expected effect is significant, both on the position of the rectus EOMs relative to the globe and their pulling directions. Numerous MRI studies indicate this side slip does not occur (Clark et al., 1997, 2000; Kono, Clark, & Demer, 2002; Miller, 1989).

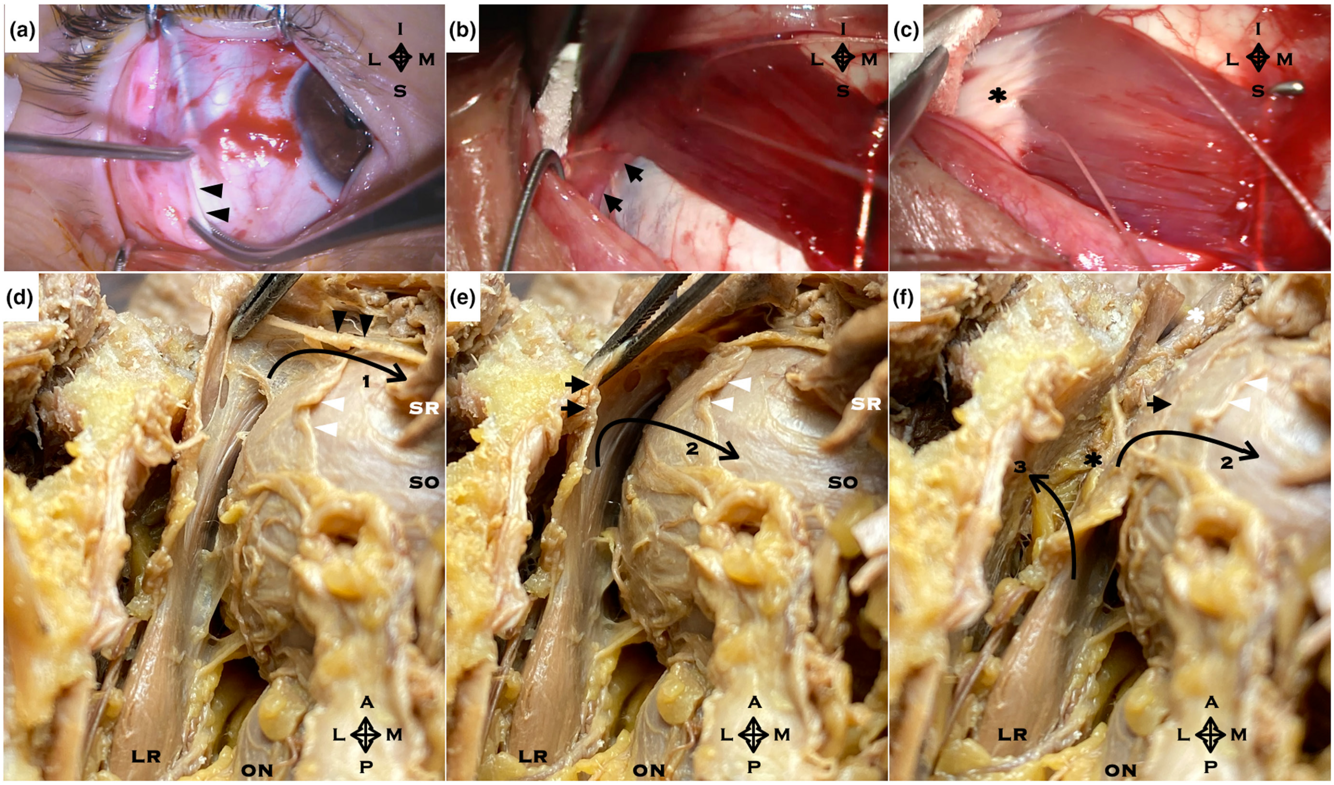

FIGURE 6 (a–c) Surgical and sequential exposure of a lateral rectus (LR) muscle (view of the surgeon on the patient's head). (d–f) The left orbit of a formalin-fixed cadaver in a superior approach dissection exposes the trajectory of the LR muscle in its relationship with Tenon's capsule, its pulley and interdependence with neighbouring structures. The figure seeks to establish a correlation between vertically arranged images: (a–d, b–e and c–f). (a) Following the engagement of the LR muscle on a surgical hook, the white anterior pulley slings are visible just posterior to the tendon insertion (black arrowheads) and easily displaced with forceps. (d) Note its arrangement concerning the globe's curvature towards the superior rectus muscle insertion (black arrowheads), bending or with the convexity towards the orbital wall (black curved arrow 1). (b) After blunt dissection of the anterior slings of the pulley from the most anterior part of the tendon, the LR-SR band (black arrows) becomes apparent more posteriorly at the level of the equator (this position is more posterior in the case of the lateral rectus relative to the medial rectus). (e, f) More robust, dense and elastic (black arrows), practically inseparable from the muscular belly with forceps (black curved arrow 2). (c) In the same position, on the external surface of the muscle, we observed a dense connective tissue strongly adherent to the muscle, corresponding to its insertion of the pulley (black asterisk). (f) When dissecting the orbit, its relationship with the corresponding check ligament (black asterisk) and its adhesion to the lateral wall of the orbit and anteriorly in continuity with the tarsus and the lateral palpebral ligament (white asterisk) are observed. The posterior end of this sleeve is shaped into slings that bend inwards towards the centre of the orbit (schematically represented by the curved arrow 3). A, anterior; I, inferior; L, lateral; M, medial; ON, optic nerve; P, posterior; SO, superior oblique; SR, superior rectus; S, superior; White arrowheads, Tenon's capsule.

Instead, these muscles are fixed within the orbit by structures aptly named "rectus pulleys." The revelation of the pulley system was a turning point in ophthalmological research. Since the pulleys constitute the functional origins of the EOMs, we cannot escape the implication that pulleys are strong determinants of EOM function. Every rectus EOM can have horizontal, vertical, and torsional actions that depend on the location and behaviour of that EOM's pulley (Demer, 2004, 2006b). Moreover, the pulleys exhibit dynamic movement influenced by the oblique EOMs (Demer, 2002, 2004, 2006b, 2007; Demer et al., 2003). This means that the pulleys, not just neural inputs, can determine certain aspects of eye movement, including torsional changes.

The clinical implications of these findings are profound. Conditions like strabismus, previously attributed solely to muscle or nerve malfunctions, can also be linked to pulley system anomalies. This has paved the way for novel surgical interventions targeting the pulleys to rectify certain forms of strabismus.

1.4 | Orbital pulleys. The guardians of ocular kinematics

So, the rectus EOMs do not follow straight-line paths from their origins to their scleral insertions. The rectus EOM inflexions in the anterior orbit constitute the functional pulleys. Anterior to the pulleys, rectus EOM paths directly track to the scleral insertions. The pulleys thus act as mechanical origins of the rectus EOMs. The line segment between the scleral insertion and pulley thus defines the EOM's pulling direction (Figures 4a and 5). Constructed of dense collagen rings approximately 2 mm in length, these pulleys surround the EOMs in a sleeve-like manner. The anterior end of these sleeves is shaped into slings that bend towards the orbital wall, whereas the posterior slings bend inwards towards the centre of the orbit (Figure 6; Demer, 2002; Demer et al., 1995, 2000; Lambert & Lyons, 2017). The anterior slings of the pulley system have been referenced as the "intermuscular septum or membrane" in classic textbooks (Duane & Jaeger, 1982; Von Noorden & Campos, 2002; Yanoff & Duker, 2004).

The internal structure of these pulleys, particularly their collagen fibrils, possesses a cross-hatch pattern, providing the pulleys with notable rigidity (Porter et al., 1996). Adding to this intricate structure are elastic fibres that surround the pulleys (Kono, Poukens, & Demer, 2002). These fibres bestow them with a reversible extensibility, crucial for anchoring the pulleys to the bones of the orbital rim, maintaining tension and ensuring the pulleys' positioning remains more anterior in the orbit. Smooth muscle tissues are notably found within these pulley suspensions and throughout the peribulbar region, creating a comprehensive lattice network (Clark et al., 1997; Demer, 2007; Demer et al., 1995, 1997, 2000; Kakizaki et al., 2010; Miller et al., 2003). A significant component of this network is the inframedial peribulbar muscle. (Miller et al., 2003) Originating from the confluence of the inferior rectus and the inferior oblique muscles, these bands traverse towards the medial rectus muscle. It's fascinating to note that these bands primarily constitute the smooth muscles situated around the inferomedial orbit (Miller et al., 2003). Its role might be pivotal in ensuring the symmetrical movement of the eye during specific complex gaze shifts, such as in elevation and depression in adduction.

These anatomical nuances are not just limited to textbooks. Surgeons can observe these structures during procedures. Following the engagement of a rectus EOM on a surgical hook, the white anterior pulley slings are visible. These tissues play little role in constraining EOM paths. The anterior pulley slings can usually be displaced posteriorly by blunt dissection, after which fine fibrous bands constituting the insertion of the OL of the EOM on the glistening white pulley suspension can be visualised just posterior to the globe's equator (Figure 6a–c). This insertion is anterior to the pulley ring, obscured by the overlying white tissue of Tenon's capsule. Clinical interventions, such as the transposition of a rectus tendon, further validate the existence and function of these pulleys. Even after the tendon's transposition, for treating lateral rectus palsy, the muscle continues its path towards its original pulley. However, the clinical outcomes can be enhanced by fixing a point on the transposed muscle's belly to the sclera near the affected EOM, effectively shifting the pulley in the direction of transposition (Clark & Demer, 2002b; Miller et al., 1993).

The intimate interaction between the EOMs and their corresponding pulleys is pivotal in the precision and consistency of eye movements. Inserting each rectus EOM's OL on its corresponding pulley translates (linearly moves) that pulley posteriorly during EOM contraction. This nuanced interplay is readily visualised through coronal MRI scans, revealing shifts in rectus EOM paths during specific tertiary gaze directions (Kono, Clark, & Demer, 2002). Moreover, the inferior oblique pulley showcases its distinct dynamism by shifting its position in response to eye movements. It moves anteriorly during upward gazes (supraduction) and shifts posteriorly during downward gazes (infraduction). This specific behaviour of the IO pulley is intrinsic to maintaining optimal control over the IO's pulling trajectory (Demer et al., 2003). The superior rectus (SR) pulley also exhibits explicit mechanical interlinkages with other pulleys (Kono, Poukens, & Demer, 2002). One such substantial linkage is a robust band connecting the lateral border of the combined SR/LPS pulley to the upper boundary of the lateral rectus (LR) pulley—LR-SR/LPS band. This connection, composed of dense collagen and elastin, demarcates the orbital section of the lacrimal gland (Figure 1b). Though not easy, this band can be separated from another, the LR-SR band, which is deep and parallel to it in its path, structurally more robust and denser, and that reinforces Tenon's capsule, forming part of the inter-pulley ring just posterior or at the equator of the eyeball (Figure 6).

Although the rectus and IO pulleys are mobile along the lengths of their EOMs, pulleys are located quite stably and stereotypically in the transverse directions. Since EOMs must transit their pulleys, and the pulleys encircle the EOMs, pulley locations may be inferred from EOM paths. Even the anteroposterior pulley locations can be determined by imaging EOM path inflexions produced by the pulleys in eccentric gaze positions. Adhering to a specific coordinate reference is vital when identifying these pulley positions. Notably, the confidence intervals for standard rectus pulleys' horizontal and vertical coordinates vary only minimally (Clark et al., 1997). The positioning of the pulleys is paramount as they effectively function as the mechanical origins for the EOMs and are proximate to the globe's centre. However, it is essential to understand that natural ageing processes introduce changes to this intricate system, notably causing the horizontal rectus pulleys to droop marginally. In contrast, the positioning of the vertical rectus pulleys remains relatively unaltered throughout one's lifetime (Chaudhuri & Demer, 2013; Clark & Demer, 2002a).

Orbital pulleys, specifically rectus pulleys, are central players in the intricate ballet of ocular kinematics. Successive rotations are not mathematically commutative in that final eye orientation depends on the order of rotations. Each combination of horizontal and vertical directions of an arbitrary sphere could be associated with infinitely many torsional positions (Demer, 2007; Lambert & Lyons, 2017). The eye, however, is constrained (when the head is upright and immobile) by a relationship known as Listing's Law (LL), a statement of classical observations that the torsion of the eye in any gaze direction is that which it would have if it had reached that gaze direction by a single rotation from primary eye position about an axis lying in a plane, Listing's plane (Demer, 2007; Lambert & Lyons, 2017; Von Noorden & Campos, 2002). LL is always satisfied if the ocular rotational axis shifts by exactly half of the shift in ocular duction. For example, if the eye supraducts by 20°, then the vertical axis about which it rotates for subsequent horizontal movement should tip back by 10°. This is called the "half-angle rule." Conformity to the half-angle rule makes the sequence of ocular rotations appear commutative to motor control centres in the brain (Demer, 2004, 2006a). Appropriate rectus pulley position implements the half-angle kinematics required by LL.

However, the pulleys could remain stationary if things were as simple as primary and secondary gazes. Yet, tertiary gazes, such as adducted supraduction, need the rectus pulleys to actively shift anteroposteriorly in the orbit along the EOM's length, so the relationship is maintained in an oculocentric reference (Demer et al., 2000). This shifting ensures that LL's principles remain intact even during compound gazes. The active pulley hypothesis (APH) further explains these shifts. The APH states that these shifts are generated by the contractile activity of the OIs of each EOM acting against the elasticity of the pulley suspensions (Demer, 2007; Demer et al., 2000; Kono, Clark, & Demer, 2002).

It becomes abundantly clear that the orbital connective tissues play a pivotal role in controlling ocular kinematics, a function not replaceable or capable of compensation by neural circuits. Even physiological pulley shifts during convergence and extreme vertical gaze are associated with significant vertical binocular misalignments during as ubiquitous a behaviour as the vestibulo-ocular reflex (Demer, 2004). It should then come as no surprise that the disease of the pulleys and their associated connective tissues would be related to predictable and much more extensive patterns of binocular misalignments. Distinct forms of pulley disease are now recognised as likely causes of strabismus. This is particularly significant because pulleys are accessible for surgical manipulation (Figure 4b) (Demer, 2006b; Demer et al., 1996).

2 | THE PARADIGM OF STRABISMUS SURGERY

Traditionally, the goal of strabismus treatment has been to realign the visual axes to eliminate diplopia or to produce, maintain, or restore binocular vision. Additionally, surgery to improve an abnormal head posture, eliminate abnormal eye movements, or restore the standard anatomical position of the eyes are well-accepted indications for surgery.

2.1 | Understanding the role of 'arc of contact'. Deciphering torque

The mechanical strength of an extraocular muscle is related to its length, arc of contact, and pulling direction. When discussing a recession, in which a rectus muscle will set behind its original insertion, it is traditionally viewed as a method of weakening the muscle's action. The effects of this procedure can be outlined in two main ways:

2.1.1 | Introducing slack to the muscle

This muscle slack causes the eye to rotate away from the recession due to reduced muscle tension (Beisner, 1971; Kushner & Vrabec, 1987). The muscle tension should be weakened in a linear dose–response fashion based on Starling's length-tension curves (Collins et al., 1975; Collins et al., 1981; Gordon et al., 1966; Starling & Evans, 1968). However, this theoretical approach has practical limitations. If we bring the insertions so close to a point where muscle relaxation is close to its maximum contraction capacity, zone I of the sarcomere practically does not exist; it virtually produces, following the all-or-nothing law, a complete functional impotence with contracture and secondary muscular atrophy (Galán Terraza & Visa Nasarre, 2012). Additionally, clinical experience suggests otherwise. Medial rectus muscle recessions greater than 8 mm frequently produce overcorrection (Kushner et al., 1994), while small medial rectus muscle recessions less than 3 mm typically produce little to no surgical effect.

2.1.2 | Reduction of the arc of contact

The maximum amount of recession that can be done on a muscle also depends on the *arc of contact*. Physiological insertion (tangential point) is different depending on the muscle considered in the primary gaze position and will vary in different situations and positions of the eye in the orbit; it lies 1.80 mm anterior to the equator of the globe in the medial rectus, 8.5 mm posterior to the equator in the lateral rectus, and approximately level with the equator in the vertical rectus (Galán Terraza & Visa Nasarre, 2012). The *arc of contact* is variable depending on the state of muscle contraction; it is less the more contracted the muscle is, and there comes a time when it disappears, which is when the physiological and anatomical insertion coincides; at this moment, the arm begins to decrease lever on which muscle traction acts (Galán Terraza & Visa Nasarre, 2012; Von Noorden & Campos, 2002).

The values of the *arc of contact* will vary with age and with axial refractive state, due in both cases to the variation in the size of the globe (Clark & Demer, 2020), and this must also be taken into account because it will condition that the quantities recession or resection maxima are different depending on whether children are small or large hyperopic (smaller eyes with a more minor "*arc of contact*") and adults or large myopic (large eyes with a more significant "*arc of contact*"). Recent MRI studies demonstrated that contrary to the *arc of contact* biomechanical model, standard and postsurgical EOMs are significantly nontangent to the globe during large ipsiversive ductions (Figure 4). In most cases, the EOM tendon thickness and post-insertional curvilinear path combined to create a substantially larger-than-predicted angle at tendon insertion with resultant greater-than-predicted loss of globe tangency (Clark et al., 1999; Clark & Demer, 2018).

Torque, or the rotational force, is pivotal to understanding the mechanical intricacies of eye movement and its associated surgical interventions. The relationship between torque and the mechanisms of eye movement, particularly in the context of EOM pulleys, is multifaceted and goes beyond traditional lever arm mechanics.

When we discuss the eye's movement, the force exerted by the muscles and the length of the lever arm defines the torque. As the

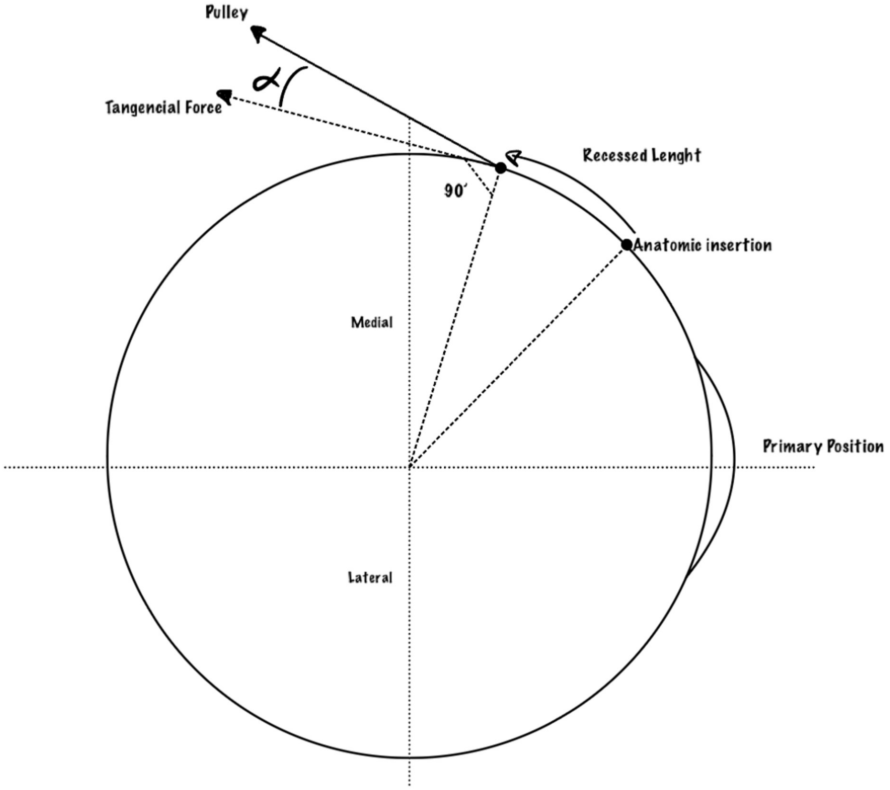

FIGURE 7 Medial rectus muscle force vectors on the globe after a recession with the inclusion of the pulley complex.

eye rotates, the lever arm shortens, reducing the torque. Boeder's findings (Boeder, 1962) further clarify this—a mere 15° of adduction can halve the arc of contact for the medial rectus, and at 30°, this arc vanishes altogether. Previously, the understanding was grounded in the belief that recessions worked mainly by altering the effective length of the muscle, thereby tweaking the torque. However, the discovery of EOM pulleys provides a novel perspective (Figures 4 and 7). Consider the pulley as the muscle's functional starting point or "origin" (Demer et al., 1995, 2000). Any recession will permanently modify the torque vector at the globe's surface, decreasing the torque for a given muscle innervation level (Clark & Demer, 2018).

Analogous to force in linear movements, torque is instrumental in producing angular acceleration in rotational mechanics. It is a vector—carrying both magnitude and direction. The lever arm (also described as the moment arm), the perpendicular distance between the force line of action and the axis of rotation, works in tandem with the force to define the torque. For the eyes, this axis is the globe's centre, and the lever arm equates to the distance between the centre and where the tangential muscle force acts, such as the medial rectus insertion point. Assuming that the pulley is static during the eye's rotation, it serves as the functional origin of the muscle, like the medial rectus. Consequently, post-recession, the net force acting on the globe rarely matches the geometric tangential force, leading to an angle between force vectors due to the pulley's influence (Figure 7; Miller & Mims, 2006). This adds another layer to the mechanics of eye movement and surgical intervention.

The traditional belief posits a linear response for every millimetre the muscle is recessed, especially in bilateral medial rectus muscle recessions (Duane et al., 1998; Starling & Evans, 1968). Yet, practice shows that the effects magnify as the muscle recedes further from its insertion on the globe. Considering pulley complexes, torque changes are exponential, shedding light on why re-recessions result in amplified effects per millimetre, thereby increasing overcorrection risks (Miller & Mims, 2006).

AUTHOR CONTRIBUTIONS

PFC designed the study and collected the data. PFC and MDM analysed and interpreted the patient data. PFC has prepared the manuscript. MDM revised it. Both authors approved the submitted version.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data have not been published and are not under consideration for publication elsewhere. All authors approved the manuscript and agreed with this submission. If the manuscript is accepted for publication, it will not be submitted for publication elsewhere.

ETHICS STATEMENT

Consent and approval to use all cadavers for educational purposes and scientific research by the Portuguese Act nº 274/99 were obtained, and all cadavers were registered within the Faculty of Medicine of the University of Porto.

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