Neuromuscular Principles in the Visual System and Their Potential Role in Visual Discomfort

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Abstract. The aim of this study was to analyse the neuromuscular arrangement in the human extraocular muscles in order to obtain a better understanding of the mechanisms behind visual discomfort associated with reading and VDU (visual display unit) work. Histological evaluation of muscle samples from 10 subjects revealed fibrous extensions from the distal insertions of rectus muscles to the orbital wall. The number of neural elements found embedded in these collagenous extensions suggests that nociceptors are present in large numbers, capable of creating pain during movements of the eye. It is reasonable to assume that these structures and other parameters described in this study can contribute to visual discomfort associated with demanding visual tasks.

Keywords: VDU-work; extraocular muscles; muscle pulleys; muscle sleeves; visual discomfort.

1 Introduction

A modern designed workplace imposes great demands on the visual system. The smooth muscle of the iris and ciliary muscle (figure1) must constantly co-contract with the striated extraocular muscles (EOMs) in order to maintain good visual perception. The co-occurrence of miosis, accommodation and convergence, which are the functions of the respective muscles, relies on a constant interaction between autonomic and somatic motor neurones in the mesencephalon of the brainstem. These neurones form the nuclear complex of the oculomotor nerve which in turn constitutes a vital component of the oculomotor system. Tuning of the neural activity in the oculomotor system is provided by sensory input through the optic nerve and ophthalmic division of the trigeminal nerve. Together these cranial nerves form a unique sensory-motor loop which enables the visual system to adapt to a wide range of light levels and viewing distances. The fact that there is no external load on the EOMs and that they do not initiate any stretch reflex [1], imply that they are not influenced by proprioception in the same manner as their somatic counterparts [2]. Based on the factors described above it is legitimate to argue that the structural organisation of the oculomotor system departures from the conventional somatic motor system.

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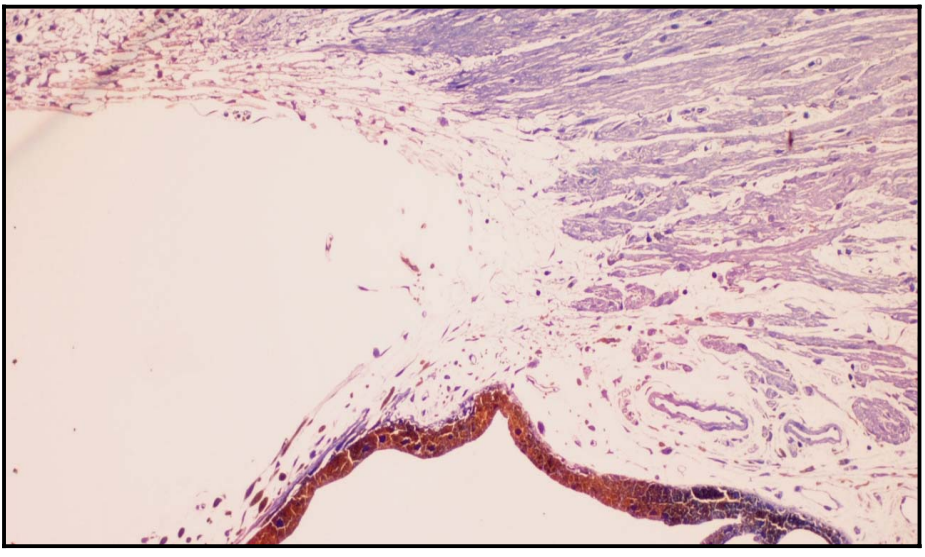

Fig. 1. The micrograph shows the pigmented surface of the iris and ciliary body and associated smooth muscle. (100x).

Hence, although detailed knowledge of somatic muscle control is essential for understanding the principals behind somatic muscular fatigue and discomfort, it may not serve as an adequate model for understanding the mechanisms behind visual discomfort.

Recent studies promote the concept that the connective tissue and neuromuscular architecture of the eye is more complex than previously assumed. Muscle fibres in the distal region of EOMs departure from the main bulk of the muscle and terminate on complex collagen structures capable of altering the angle of the muscle insertion during eye rotation. These structures have been referred to as muscle pulleys [3] and muscle sleeves [4]. The structural organisation of pulleys/muscle sleeves is not fully understood but their proposed role in oculomotor control suggests that these structures might also play a role in muscular fatigue and associated discomfort.

The purpose of this study was therefore to examine the neuromuscular structures of the orbit, histologically, and thereby obtain a better understanding of the neuromuscular mechanisms behind visual discomfort.

2 Material and Methods

EOMs were dissected from 10 human subjects of both sexes (1 day-90 years). Samples were obtained either following enucleation or post-mortem. All specimens were obtained in conformity with legal requirements. None of the patients had any history of binocular vision abnormality or neuromuscular disease. After the muscles were dissected from the eyes they were immersed in 2% glutaraldehyde buffered to pH 7.4 with sodium cacodylate, most of them with a post-operative/post-mortem

delay of less than 5 hours. Muscles with the complete distal musculotendinous junctions were selected for study of the collagenous architecture and search of tendon receptors.

The tissues were transferred from fixative to dissecting fluid (buffered sucrose) for 24 hours, washed, then immersed in a solution of osmium tetroxide for 1 hour. After washing they were dehydrated in graded mixtures of ethanol with water, initially in 50%, followed by 70%, 90% and finally absolute alcohol (with a duration of 20 min in each). Before embedding, the muscle samples were cleared with xylene for one hour. They were then transferred to a solution of equal amounts of xylene and Araldite for 30 minutes. At each stage the samples were left in a specimen rotator. They were finally left rotating overnight in pure Araldite resin. The specimens were embedded in Araldite-filled trays which were incubated at 52°, for 24 hours. Transverse sections of 0,75 μm and 75 nm thickness, were cut on a RMC ultramicrotome for light and electron microscopy respectively. Semi thin sections were stained with toluidine blue after removal of Araldite with sodium methoxide followed by a methoxide diluent, acetone and distilled water. Sections for electron microscopy were stained in a solution of uranyl acetate and ethanol for 20 minutes, followed by 20 minutes in a solution of lead citrate and sodium hydroxide.

The semi thin sections were collected with intervals of 50 μm. Measurements of structures were taken through the light microscope by the aid of a calibrated microscope eyepiece graticule. The obtained data was later confirmed by using data analysis. Sections were also cut through tendon with 50 μm intervals until nerves were identified. Serial sections were obtained following identification of neural elements. Ultra thin sections for electron microscopy were collected with regular intervals.

3 Results

Observations made in the current study confirmed many of the unique features of extraocular muscles previously described by others. Slender tendons leave the orbital surface of rectus muscles at regular intervals and enter connective tissue structures located near the equator of the eye, as illustrated in figure 2. These collagen structures, referred to as pulleys [3] or sleeves [4] are continuous with the fascial canopy of the globe, the fascia bulbi. The thickest muscle sleeves were found to contain smooth muscle and were associated with the medial rectus muscles, the muscles responsible for convergence of the eyes. The compact mass of collagen which forms the orbital side of the sleeve in the medial rectus muscles were attached to the orbital wall by fine ligaments. Consistent with previous observations [4], these ligaments were found looping behind the orbicularis muscle to reach the periosteum. In the current study, using methods of high resolution, well defined circular structures identified as axoplasm were found embedded in these ligaments. Serial sections showed that these axons were initially small myelinated or unmyelinated axons, 1-3μm in size, which with regular occurrence tapered off and ended as free nerve endings resembling the structural organisation of nociceptors (figure 3).

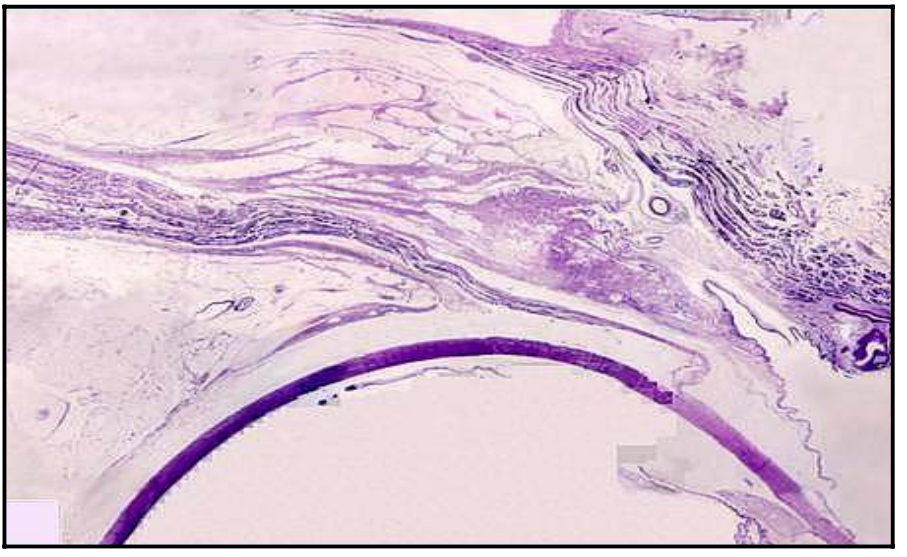

Fig. 2. The collage of micrographs shows the distal end of a human rectus muscle inserting on the globe. A number of muscle fibres departures from the main bulk of the muscle and terminate on a sleeve of connective tissue. Extensions from the sleeve attaches to the orbital wall.

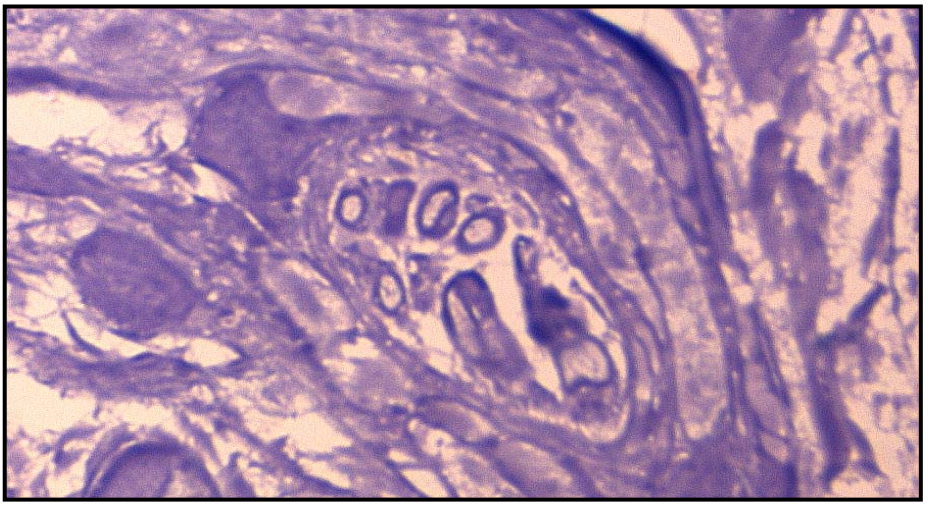

Fig. 3. The micrograph shows small unmyelinated and myelinated nerve fibres embedded in the collagenous tissue of the fibrous extensions. A number of these axons tapered off progressively resembling the structural organisation of nociceptors. (1000x).

Nerve terminals were also found associated with distal tendons of slow contracting, multiply innervated Felderstruktur fibres (figure 4). They conformed to the structural organisation of sensory receptors previously described as myotendinous cylinders [5, 6]. Analyses of the muscle fibre population in this region of the muscle revealed large individual differences in the number of muscle fibres and associated receptors. Previous studies have promoted the view that there is a division of labour between the fibres in human EOMs [7] and there is a general agreement in the literature that the Felderstruktur fibre is responsible for the slow contractions needed during reading. The current study showed that the content of Felderstruktur fibres, previously assumed to constitute 20% of the fibre population [7], ranged from 15-30%. These results confirmed previous observations made by the authors [8, 9].

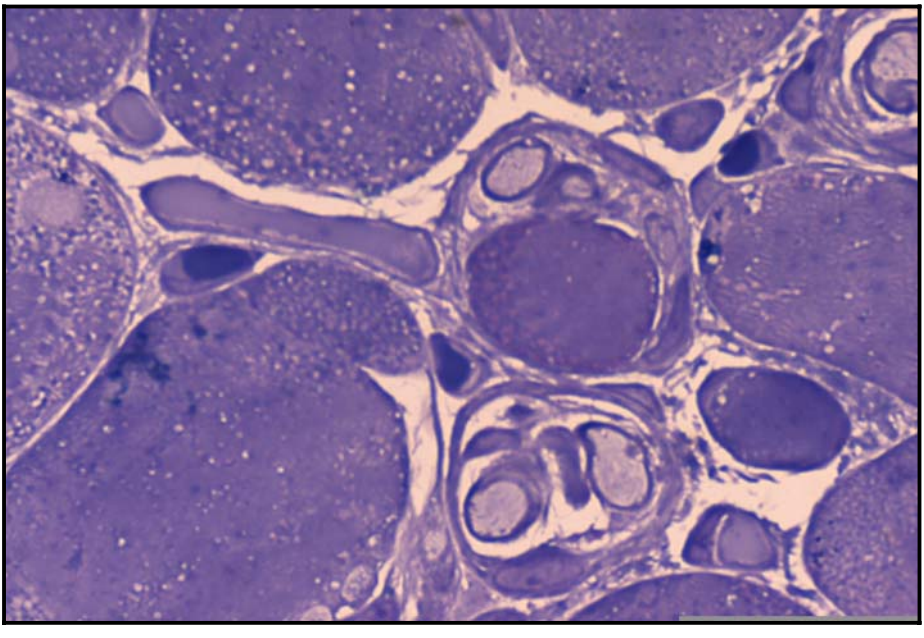

Fig. 4. The micrograph shows two Felderstruktur fibres surrounded by larger fast contracting Fibrillenstruktur fibres. The Felderstruktur fibre is slow contracting and responsible for prolonged contractions during reading and VDU work. The Fibrillenstruktur fibre is responsible for fast saccadic eye movements. (1000x).

In muscle samples from the mature subjects these muscle fibres displayed age related changes, such as accumulation of lipofuscin (figure 5), Ringbinden fibres (figure 6) and fragmentation of myofilaments (figure 7). Reduction in muscle fibre numbers were a generally occurring feature of in all the mature muscle samples. These findings confirm previous observations [10, 11, 12, 13, 14].

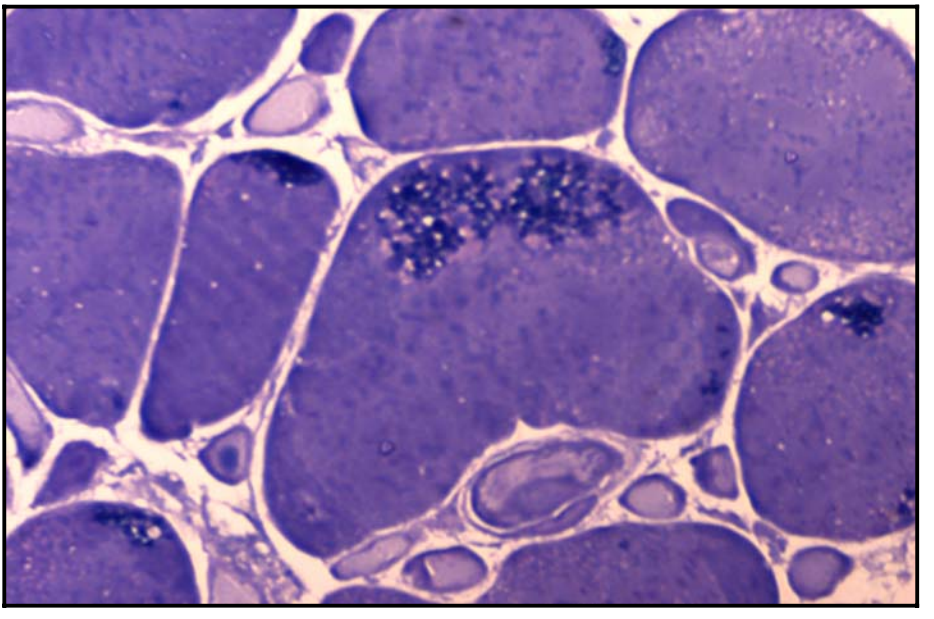

Fig. 5. The micrograph shows a muscle fibre with accumulation of lipofuscin. (1000x)

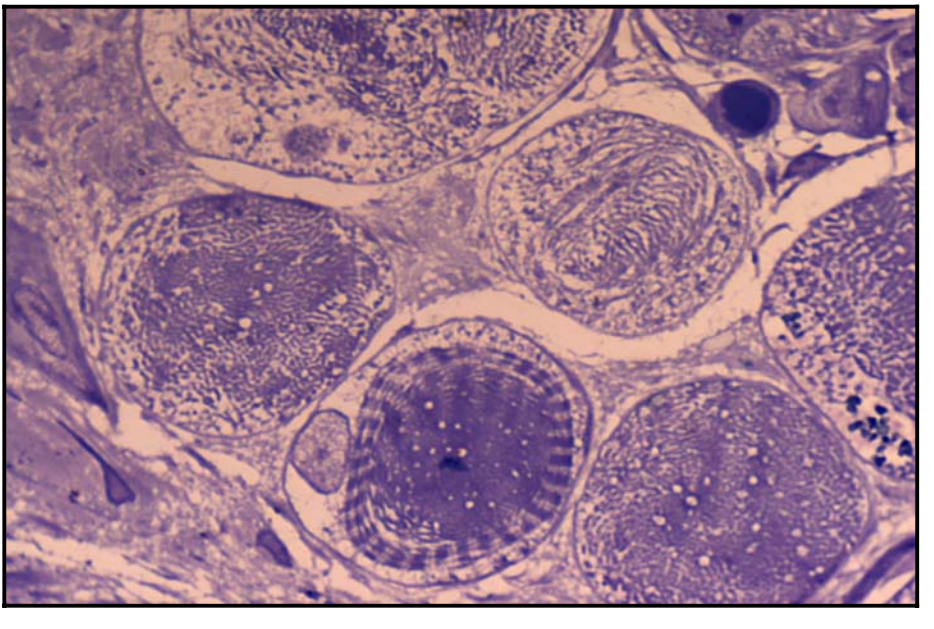

Fig. 6. The micrograph shows a transverse section of a Ringbinden fibre. (1000x)

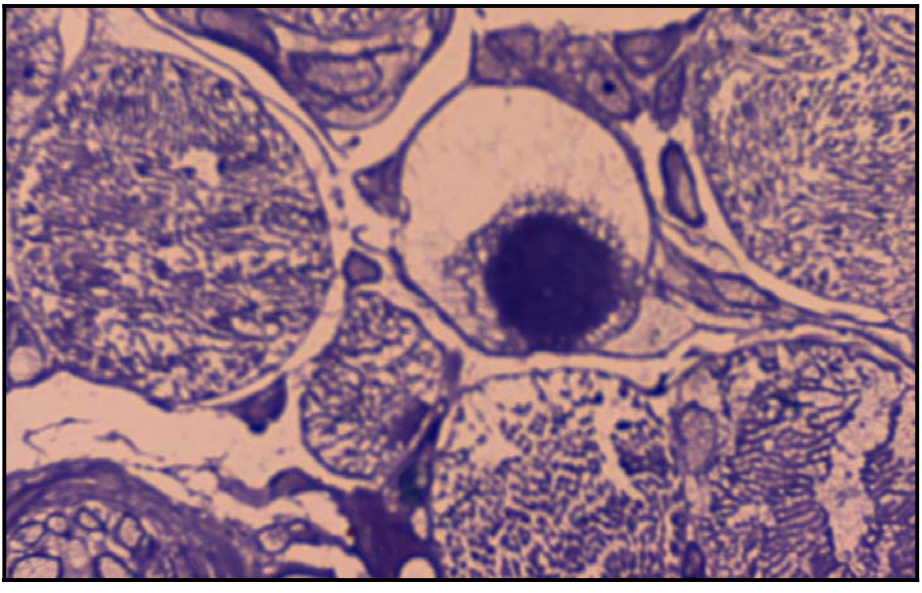

Fig. 7. The micrograph shows loss of contractile material in a mature muscle fibre. (1000x)

4 Conclusion

Sustained near-visual work, such as reading and VDU work, imposes demands on the visual system which can cause visual discomfort. Based on the observation in previous and current studies, it is legitimate to argue that the following neuromuscular parameters may contribute to such discomfort:

1. *Variations in fibre population.* Prolonged near-visual activity requires long standing contractions of a sufficient number of muscle fibres with appropriate physiological properties. The current study revealed large individual variations in the number of such fibres. A low concentration of these so-called Felderstruktur fibres will not only reduced the patient's capacity to maintain fixation, but also affect the interaction between accommodation and convergence. Furthermore, the Felderstruktur fibre is associated with receptors providing proprioceptive feedback. A reduction in afferent signals may induce instability in the oculomotor system, not only because of reduced afferent signals from the oculorotary fibres but also from the fibres terminating on the muscle sleeves. A low number of muscle fibres with the required physiological properties will demand an increased effort from the remaining fibre population. A compensatory contraction will increase the tonus in the muscle which in turn will narrow the endomysial space where many of the muscular nociceptors are located. From this follows that long lasting compensatory contractions represent a potential source of visual discomfort.
2. *Head movements and ocular rotation.* The Medial Longitudinal Fasciculus (MLF) is an extensive pathway linking the vestibular nucleus with the oculomotor system. Axons in the MLF influence directly or indirectly the neural activity in all of the

oculorotary cranial nerves. Habitual head posture during near-distance work may therefore have functional implications and be a potential cause of visual discomfort. The compensatory ocular rotation which is induced by the vestibular input can cause an increased tonus in the extraocular muscles and result in deformation of the free nerve ending in a similar manner as promoted in the section above (nr 1).

3. *Collagen connections to periorbita and dura mater.* It is generally accepted that free nerve endings, branching to form plexuses, are present in many tissues including tendons and the meningies of the central nervous system. The duramater enters the orbit through the optic canal and divides at the site of entry. One part of the duramater forms the periorbita, lining the orbital wall, while the other extends forward and envelopes the optic nerve all the way to the posterior pole of the eye. The origin of the extraocular muscles forms a ring of collagen around the optic canal and fuses with the collagen of the periorbita. Tension on the periorbita through rotation of the eye is a well documented source of orbital pain and is believed to be the main cause of discomfort in cases of inflammation of the orbital apex such as retrobulbar neuritis. The filaments connecting the muscle sleeves with the frontal part of the orbital wall, as described in current and previous studies can arguably apply a similar tension on the periorbital tissue. The presence of embedded neural elements within the filaments as well as in the periorbita suggests that the level of tension does not necessarily have to be excessive in order to produce a sensory signal. Constant changes in working distances will create a pull on the collagen fibres running between the globe and orbit. It is reasonable to assume that if this activity persists over longer periods of time it may trigger the embedded nociceptors, creating sensation of discomfort and/or pain. Free nerve endings cannot always be discriminated from passing autonomic nerve fibres with certainty and the notion that some of the observed fibres terminated on blood vessels or smooth muscle cells cannot be dismissed. However, since no such structures were observed in the vicinity of where the axons terminated, confusing the two seems unlikely.
4. *Age-related changes.* The current study suggests that the potential discomfort in relation to VDU work may increase with age due to degenerations in the neuromuscular architecture.

Although visual discomfort is a subjective experience of a multi-factorial origin, the current histological study has arguably revealed some of the potential underlying neuromuscular mechanisms.

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