Isometric force measured in human horizontal eye muscles attached to or detached from the globe

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Abstract

Purpose: To compare force development in single, horizontal human eye muscle during saccadic eye movements, first when the muscle was still attached and later when it was detached from the globe.

Methods: Eleven horizontal muscles of 8 patients were examined during surgery under topical anesthesia for concomitant strabismus. None of the muscles examined had been operated before. Isometric muscle tension was recorded with a strain gauge system, to which the muscle tendon was attached by a silk suture. The subjects made saccadic eye movements with the non-recorded eye by fixating LEDs in the center and at 10, 20 and 30 degrees horizontally to each side. Continuous and stepwise saccades were produced. In the tension signals, peak tension (Fp), steady tension (Fs), the ratio Fp/Fs was measured. Statistical analysis was done with MANOVA.

Results: The values of Fp, Fs and Fp/Fs at different amplitudes of the saccadic eye movements were compared in the attached and the detached muscle. There were no consistent statistical differences between the values obtained in the two conditions.

Conclusions: The muscle force development, measured at the tendon, was the same in muscles attached to the globe and in muscles free from the globe. Thus isometric muscle tension can be adequately recorded in muscles still attached to the globe, which increases the possibilities to study contractile properties of various eye muscles during ophthalmic surgery procedures performed under topical anesthesia.

Key words: Human extraocular muscle, isometric tension, attached and detached muscle.

Introduction

Direct measurements of tension during contraction of human eye muscles have been done both in isometric and isotonic conditions by means of implanted force transducers[1,2]. Indirect measures of eye muscle tension have been performed with non-invasive techniques using a tension sensitive forceps[3] or applying a force sensitive probe to a contact lens attached by suction to the globe[4,5]. The information obtained has been of value in evaluating pathological factors underlying both concomitant and incomitant strabismus [6,7].

Measurements of eye muscle tension in normal subjects have been done with the indirect techniques [3,5,8]. The invasive techniques have been used only during strabismus surgery under topical anesthesia, limiting the measurements to include strabismic muscles detached from the globe [1,2].

The idea of recording tension in eye muscles still attached to the globe has been raised by Goldberg & Shall [10]. They wanted to test whether the tension development measured at the tendon was different depending on if the muscle was attached to the globe and the tendon kept in normal configuration as a wide band, or if the muscle was detached and the tendon was converging to one point. From their data obtained in the lateral rectus muscle of the cat, they concluded that both whole muscle and motor unit contractile characteristics under isometric conditions were consistent regardless of whether the muscle was detached or left attached to the globe.

We have measured isometric tension development in human strabismic eye muscle that was first attached to the globe and later detached. If the contractile properties corresponded in the two states, it would be possible to measure tension in normal eye muscles during eye surgery under topical anesthesia without detaching the muscle from the globe. A preliminary report of the findings has been presented[11].

Material and Methods

The measurements were done in 8 adult patients, aged 19 to 53 years with a mean age of 34.3 years. Four of the patients were females and four males. Six of the patients had primary exotropia and two primary esotropia. None of them had been operated for strabismus before. The patients gave their informed consent to have tension of the eye muscles recorded during strabismus surgery under topical anesthesia.

Premedication before surgery was done in two patients by intravenous injection of Midazolam 5 mg/ml, but not in the other six patients. The usual preparations for eye muscle surgery were done and the eye was anesthetized with Oxibuprocain 4 mg/ml in drops before opening the conjunctiva and with Ropivacain 2mg/ml in drops after opening of the conjunctiva and when needed during surgery. The muscle tendon was exposed and a silk 5-0 suture was secured into the tendon. The suture was tied around a very stiff probe of stainless steel equipped with strain gauges (Showa N51-FA-1-120-11). The direction of the probe was adjusted perpendicular to the suture and the pulling direction of the muscle. The strain gauges were applied to the probe in two pairs, allowing recording of tension in two directions perpendicular to each other. The probe was clamped to the operating table with a stand that allowed both large adjustments and finer manipulations with a micrometer, at the level of a tenth of a millimeter. The probe was covered with a sterile surgical glove, and the stand with sterile draping. A schematic picture of the experimental set up during surgery is shown in Fig 1.

The resonance frequency of the probe when attached to the operating table was 1.1 Hz.

The signal from the strain gauges were amplified in a bridge coupled amplifier and fed into a computer for filtering and for calculation of the force vector from the two channels of force recording. All tension signals were displayed in real time on the computer screen.

The recording time was set at 60 sec with a sampling frequency of 500 Hz.

The initial force of the muscle was adjusted to about 10 g with the muscle in the off direction of muscle pull. In order to achieve this position, the probe position was adjusted with the micrometer on the probe stand.

Tension changes in the recorded muscle were produced by means of saccadic movements performed by the non-recorded eye. This eye fixated light emitting diods (LED) positioned in the direction straight ahead and at 10, 20 and 30 degrees to the right and left in the horizontal directions. The viewing distance from the eye to the LEDs was 114 cm.

Fig. 1 Schematic illustration of the isometric tension recording from the detached lateral rectus muscle, shown in side and front view. Fixating lighted targets are presented for the non-recorded eye at different positions in the horizontal direction. Tension is measured with strain gauges on a steel probe in two directions perpendicular to each other, allowing the force vector in the pulling direction to be calculated.

Saccadic eye movements were produced in two modes. In one part of the recording the movements started from the off-direction of the measured muscle, i.e. with the fixating, non-recorded eye deviated 30 degrees into that direction. The fixating eye performed a series of 10 degree continuous saccadic movements from the off-direction into the on-direction of the recorded muscle and back again, i.e. a full loop of saccadic movements within the 60 sec period of recording.

In the other part of recordings, the fixating eye performed stepwise saccadic movements from the straight ahead position to positions at 10, 20 or 30 degrees into the on-direction of the recorded muscle.

In the recordings of tension development during continuous and step-wise saccadic movements, measurements were done only in the on-direction of muscle action. Values of the peak of the tension change (Fp), and of the tension 3 sec after the peak of tension change, denoted steady state tension (Fs), were analyzed. The measurements in the two different recording modes are shown in Fig 2 for continuous saccadic movements, and in Fig 4 for stepwise movements. The ratio of Fp/Fs in the on-direction of muscle contraction was also evaluated.

Data were obtained from 11 muscles, 8 lateral rectus and 3 medial rectus muscles. The recordings were done first with the muscle tendon still attached to the globe. After the full recordings of continuous and step-wise saccadic movements had been collected, the tendon was cut, the initial muscle tension was set by adjustment of the probe position, and the repertoire of saccadic movements was repeated with the muscle detached from the globe. Recordings were obtained in the operating theatre of the Ophthalmology Service of the University of Bologna.

The study, complied with the tenets of the Declaration of Helsinki, was approved by the Ethical Committee, Policlinico S. Orsola-Malpighi, University of Bologna.

Results

Continuous saccadic movements

An example of tension development during continuous saccadic movements is given in Fig 2. The data were obtained from the lateral rectus muscle in a patient with exotropia. The force development recorded in the attached muscle (black line) is almost identical in shape to that in the detached state (gray line).

Fig. 2 Isometric tension from a lateral rectus muscle of a patient with exotropia, recorded during continuous saccadic eye movements. Recording is started in a position of the fixating non-recorded eye at 30 degrees in the off-direction of the recorded muscle. Initial tension has been adjusted to about 10 g. The fixating eye is moving in 10 degree steps from an eye position 30 degrees in the off-direction of the recorded muscle, up to 30 degrees in the on-direction, and back again, over more than one cycle. The black curve represents tension with the muscle still attached to the globe, and the gray curve with the muscle detached. Fp and Fs represent peak tension and steady state tension, respectively. The total recording time is approximately 60 seconds for the detached and 50 sec for the attached muscle.

Fig 3 shows the values of Fp and Fs of the muscle shown in Fig. 2, at different eye positions during saccadic activity in the on-direction of the muscle. A slightly lower tension was observed in the attached muscles in comparison with the detached state.

Fig. 3 Peak tension (Fp) and steady state tension (Fs) of saccadic activity in the on-direction of the muscle shown in Fig 2. The recordings from the attached muscle are marked with black symbols, and the data from the detached muscle with gray symbols.

<u>Step-wise saccadic movements</u>

The recordings in Fig 4 show the tension development in the lateral rectus muscle of another patient with exotropia. Recordings obtained in the attached and detached muscle are superimposed. The tension values in the attached muscle are slightly lower than in the detached muscle, both for Fp and Fs.

Fig. 4 Isometric tension from a lateral rectus muscle of a patient with exotropia, recorded during step-wise saccadic eye movements from the primary position to 10, 20 and 30 degrees in the pulling direction of the muscle and back, two or three times for each position. The black curve was obtained with the muscle attached to the globe, and the gray curve with the muscle detached. Fp and Fs represent peak and steady state tension, respectively. The initial muscle tension was set at 10 g, with the fixating eye directed 30 degrees in the off-direction of the recorded muscle. The recording time is approximately 60 sec for each condition.

In Fig 5, Fp values during the on-direction are plotted for all muscles recorded, both in eso- and exotropia, and in medial and lateral rectus muscles. The diagram of Fig 5A shows values for Fp in the attached state and Fig. 5 B the Fp values in the detached condition.

Fig. 5 Family of curves representing peak tension (Fp) values during step saccadic movements to position at 10, 20 and 30 degrees in the on-direction of the recorded muscle. The results in the attached muscle is shown in A and the results in the detached muscle in B. The different symbols indicate each of the twelve muscles.

In Table 1 the mean values of Fp, Fs and Fp/Fs values are shown for all muscles in the attached and detached states, respectively. The Multivariate Analysis of Variance for repeated measures did not show statistically significant differences (p = .221) between attached and detached muscles for the three parameters.

Table 1. Mean values of peak tension (Fp), steady state tension (Fs) and the ratio Fp/Fs, recorded during saccadic movements of 10, 20 and 30 degrees, of all muscles in the attached and detached conditions . The values of Fp and Fs given in grams.

	Attached			***Detached***		
	Fp	**Fs**	**Fp/Fs**	**Fp**	**Fs**	**Fp/Fs**
10	24.0	11.9	2.5	28.2	12.4	2.5
20	40.1	25.0	1.7	40.2	21.2	2.0
30	50.6	32.2	1.7	52.5	33.0	1.8

Discussion

These recordings of isometric tension development from the horizontal eye muscles in human strabismic subjects showed that is not necessary to detach the eye muscle from the globe for accurate representation of the isometric tension changes in saccadic eye movements. Detaching the muscle from the globe did not significantly alter the muscle responses in comparison with recordings from the attached muscle. This is in agreement with the findings in the lateral rectus muscle of the cat, reported by Goldberg & Shall [10].

In order for comparable recordings to be made in the attached and detached states of the same muscle, the length of the recorded muscle was adjusted, so that it had a resting tension well above zero and preferably around 10 g in the most relaxed position of the muscle. Collins and coworkers[2] reported that the minimum isotonic tension in human eye muscle is 8 - 12 g in the gaze direction outside the field of action of the muscle. This resting tension was thought to originate in the orbital layer of the eye muscles, where some of the fibers are continuously active, even in the most relaxed position in the muscle.

Measurements of peak tension during saccadic movements were done at the initial phase of the tension change in the on-direction of muscle activity. During muscle relaxation during saccadic movements in the off-direction muscle tension dropped quickly, but the shift of tension could not be measured in a reproducible manner, and measurements of forces during this phase were not done.

Measurements of steady state values were obtained at 3-4 seconds after the peak of the saccadic tension. This may be to short to reach true steady state tension, but the time at the measurement represented a trade off between obtaining a reliable steady state value and reaching a full set of recordings at different fixation positions during the 60 second period of recording One minute was considered a reasonable period for attentive fixation performance, demanded of the patient under the prevailing surgical conditions.

The dynamics of saccadic tension development could be estimated from the amplitude of peak tension and the ratio of peak tension over steady state. The speed of the tension change in the attached muscle could be expected to be lower in the attached state than the values in the detached condition, since the attached muscle was still in contact with the globe, which would represent a mechanical load on the muscle. However, the values of Fp and Fp/Fs were the same in both the attached and detached conditions, showing that measurements in the attached muscle reflected the isometric tension development during saccadic eye movements as accurately as measurements from the detached muscles. This implies that recording of tension changes in an individual eye muscle can be accurately done also with the muscle attached to the globe, which quite markedly will increase the possibilities to collect information of force production in different eye muscles, in subjects with normal eye motility as well as in subjects with different types of strabismus and other eye motility abnormalities.

Recently it has been shown that extraocular rectus muscles are surrounded by muscle pulleys, structures that are composed of connective tissue and also of smooth muscle[12,13]. The pulleys have been shown in studies with magnetic resonance imaging to determine the effective pulling direction of the extraocular rectus muscle[14]. A redirection of the line of pull by detaching the muscle from the globe might in our studies have affected the dynamics of force development during the saccadic activation of the muscle. However, no differences in dynamic force behavior were noted in recordings from attached and detached muscles. The effects of the pulley system on muscle static behavior could not be accurately determined, since measurements of absolute tension could not be done, but the initial force was set at about 10 g in the off-direction of the recorded muscle[2].

The muscle properties recorded in this study were obtained in subjects with concomitant strabismus, of the convergent (esotropia) or the divergent type (exotropia). None of the subjects had been operated for strabismus before. Previous studies with recordings both directly from the muscles[1,2] and indirectly over a forceps[3], or with a suction contact lens[5,7], have not indicated that mechanical or contractile properties vary between strabismic and non-strabismic horizontal eye muscles. It is therefore assumed that the results obtained in this study were representative also for normal human eye muscle function.

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Fig.1

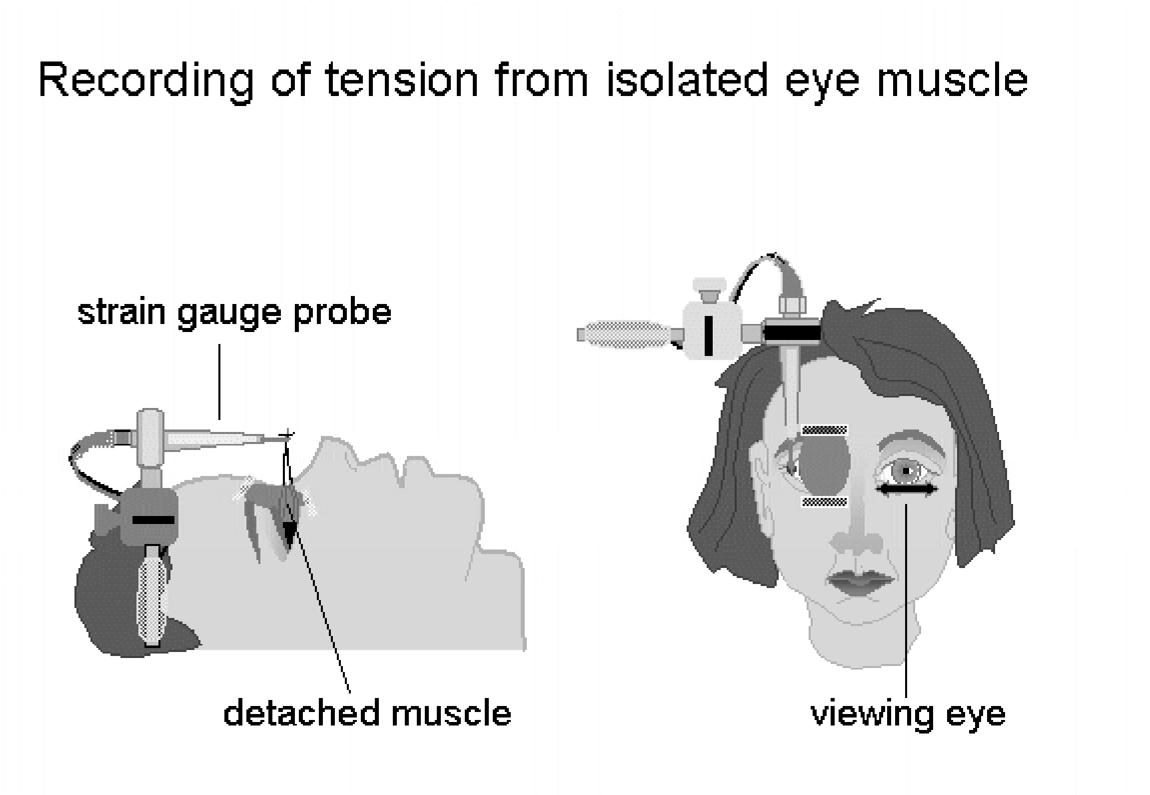
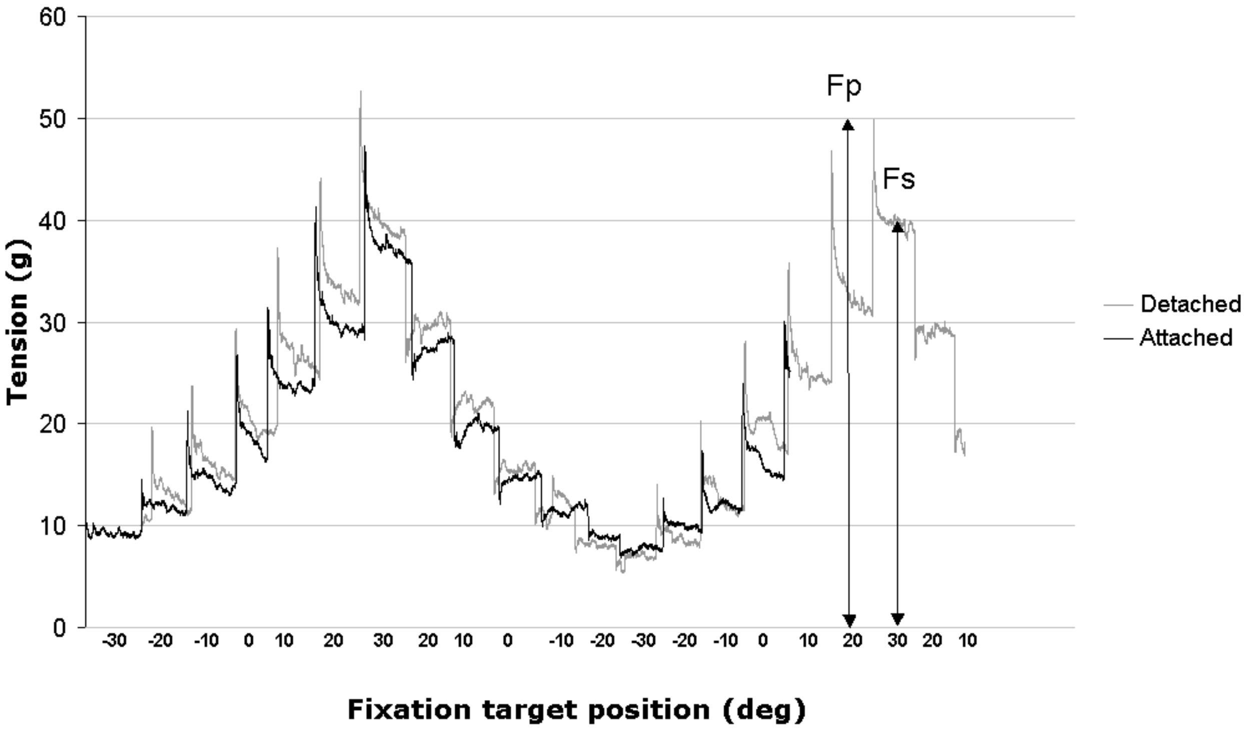
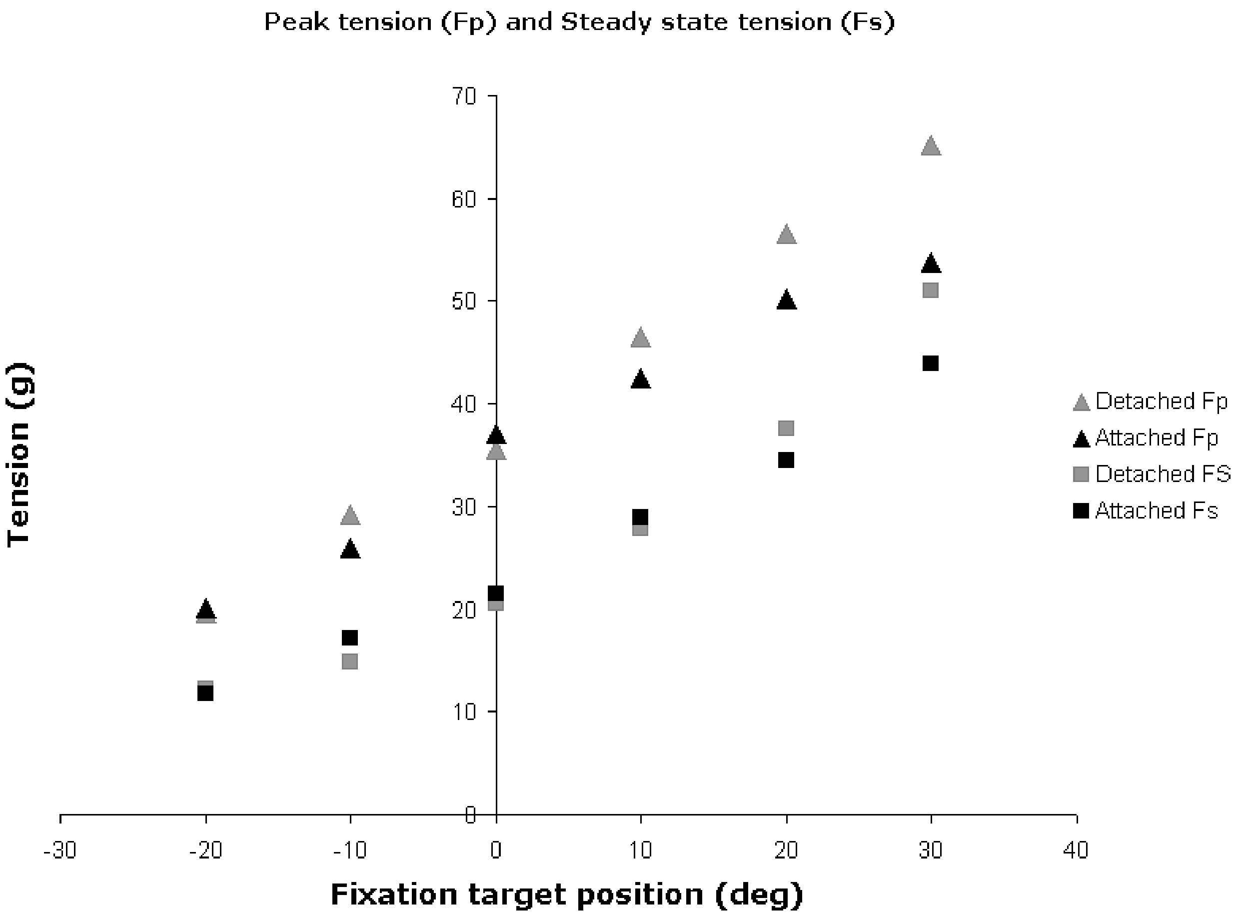

Recording of tension from isolated eye muscle
strain gauge probe
detached muscle
viewing eye

Fig. 2



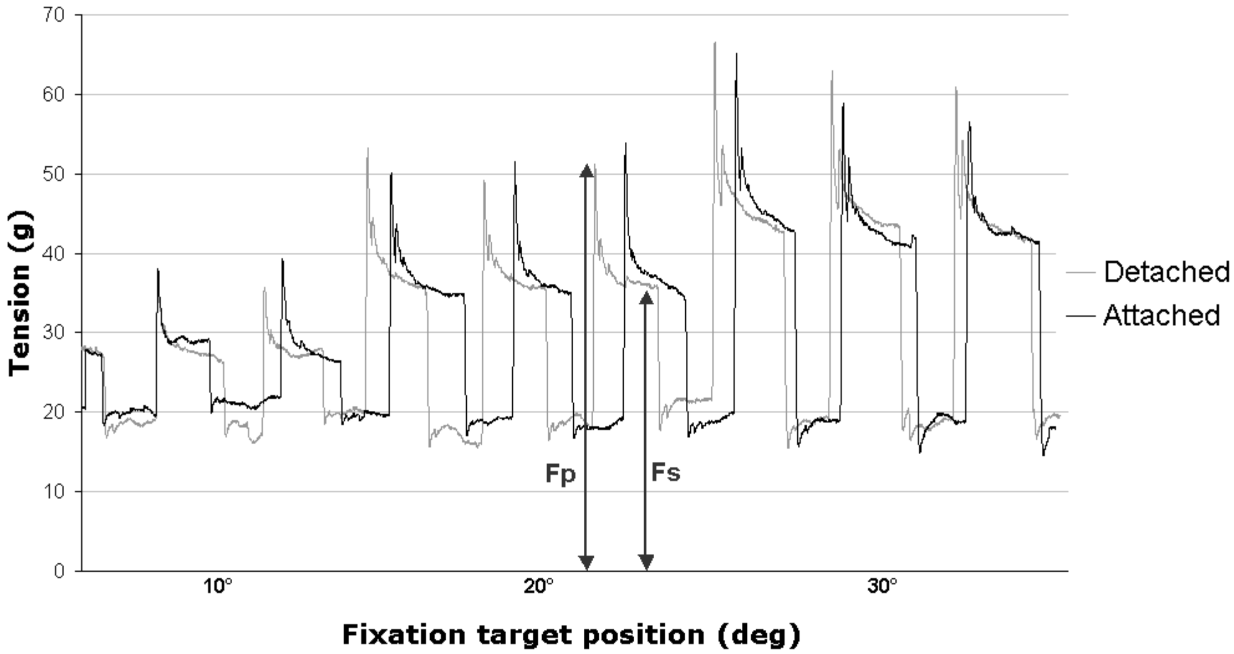
60
50
40
30
20
10
0
Tension (g)
Fp
Fs
Detached
Attached
-30 -20 -10 0 10 20 30 20 10 0 -10 -20 -30 -20 -10 0 10 20 30 20 10
Fixation target position (deg)

Fig. 3



Peak tension (Fp) and Steady state tension (Fs)
Tension (g)
70
60
50
40
30
20
10
0
-30
-20
-10
0
10
20
30
40
Fixation target position (deg)
Detached Fp
Attached Fp
Detached FS
Attached Fs

Fig.4



70
60
50
40
30
20
10
0
Tension (g)
10°
20°
30°
Fixation target position (deg)
Fp
Fs
Detached
Attached

Fig. 5A

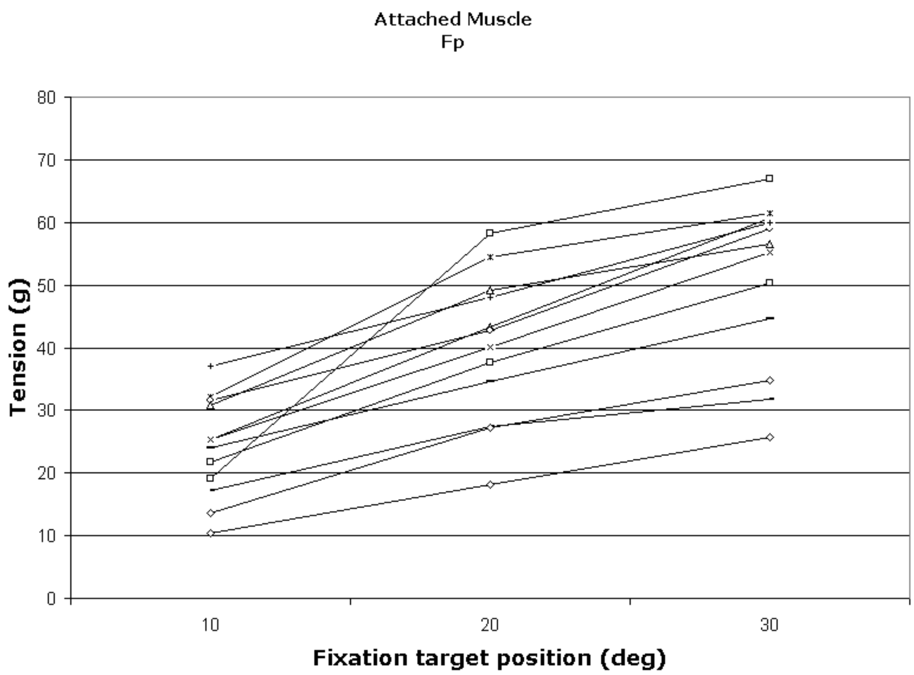
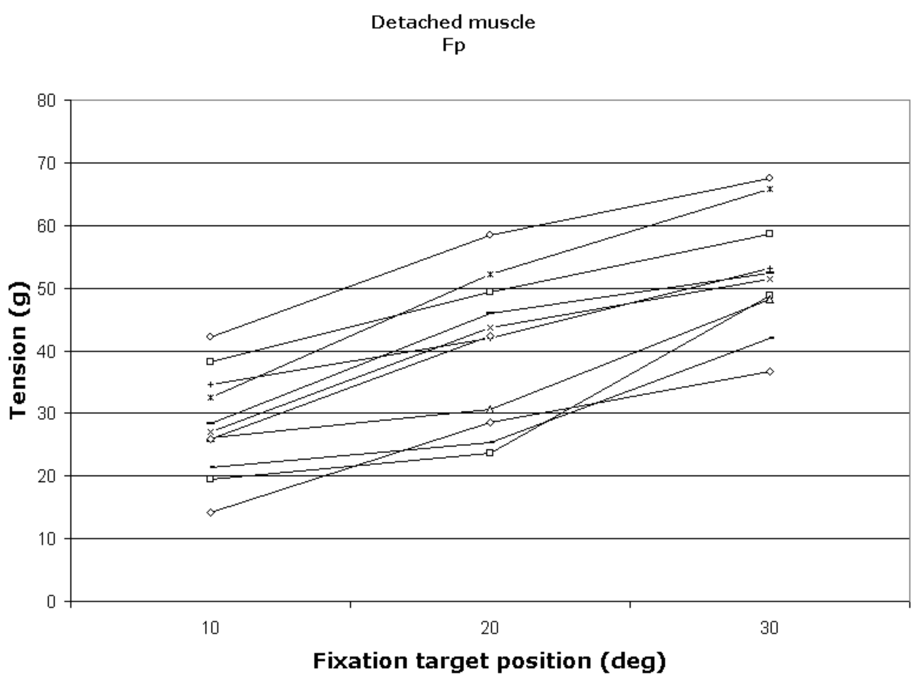

Attached Muscle
Fp
80
70
60
50
40
30
20
10
0
Tension (g)
10
20
30
Fixation target position (deg)

Fig. 5B


Detached muscle
Fp
80
70
60
50
40
30
20
10
0
Tension (g)
10
20
30
Fixation target position (deg)