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Muscles within Muscles: the classical triphasic EMG burst and its applicability to segments of large radiate agonist/ antagonist muscles

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Keywords – segment, pectoralis major, latissimus dorsi, deltoid, triphasic EMG burst, agonist, antagonist.

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Abstract

The purpose of the current study was to determine if the classically described triphasic EMG burst was applicable in describing the EMG patterns across the breadth of three large radiate muscles during the production of a rapid shoulder joint movement. Miniature (6.5 mm inter-electrode distance) bipolar surface electrodes were placed across the breadth of the pectoralis major (6 off), latissimus dorsi (6 off) and the deltoid (7 off). Subjects performed a series of rapid shoulder joint adduction movements (< 400 msec) against the resistance of a free weight and pulley apparatus whilst seated in an experimental chair. EMG data sampled from the multiple recording sites of the three muscles identified four different types of EMG waveforms. This was based on the presence, or absence, of multiple bursts, the length of each burst and the level of the silent period between bursts from the same segment of a muscle. The four bursts included a one-burst pattern, a one-continuous burst pattern, a two-continuous burst pattern and a two non-continuous burst pattern. Upon further analysis it was established that a relationship existed between the type of burst displayed by a segment and the functional role of that segment (prime mover, synergist, primary or secondary antagonist), hence a uniform type of burst pattern was not apparent across the breadth of the agonist (pectoralis major and latissimus dorsi) and antagonist (deltoid) muscles. It was evident that the triphasic EMG burst was most applicable for the EMG patterns arising from the prime mover segments of the pectoralis major and the latissimus dorsi and the primary antagonist segment of the deltoid. In conclusion these results suggest that caution is warranted if stating that popular motor control theories [10,11] based on EMG patterns produced by small agonist and antagonist muscles during rapid limb movement, apply to all segments of large radiate muscles. Further research is needed to validate this statement.

Introduction

A "triphasic" pattern of EMG activity is a feature of the activation patterns appearing in agonist and antagonist muscles during rapid limb movement. This "triphasic" pattern arises due to an initial burst of activity in the agonist muscle (Ag1), which initiates the movement, followed by a silent period during which the antagonist (Ant) becomes active, with the agonist sometimes being activated again (Ag2) at some point after the initial activation of the antagonist. This three-burst pattern (triphasic) of EMG activity involving antagonistic muscles is thus characteristic of the neuromotor control of rapid limb movements less than 400 ms duration and is considered to be a '*modus operandi*' for these types of movements [1,6,9,12,14,17].

The above-mentioned studies that examined the triphasic EMG burst have typically utilised one electrode pair for both the agonist and antagonist muscles. The EMG waveforms from these studies are therefore derived from a small portion of a large muscle or a large portion of a relatively small non-radiate muscle, such as the biceps brachii, but never from the entire breadth of a large radiate muscle using multiple electrodes. If an agonist muscle were to be considered functionally homogenous it would be expected that the same 'two non-continuous burst' pattern (Ag1 and Ag2) with a silent period in the middle be apparent across the breadth of the muscle. If only some segments of the agonist, the prime mover segments for example, are displaying two bursts or there are differences in the temporal or intensity values of the two bursts then it could by implied that this is indicative of differences in feedback and control strategies amongst segments of the same muscle. The same reasoning would apply to antagonist muscles that have typically displayed a 'one-burst' pattern (ANT)[1]. Therefore, it seems justified to have a closer investigation and analyse the "morphology" of the triphasic EMG burst pattern arising from large radiate skeletal muscles. If differing agonist and antagonist waveforms do become apparent from the multiple agonist and antagonist electrode sites then movement control expressed in terms of whole muscle activation patterns is clearly misleading and not totally accurate.

The aim of the present study was thus to determine whether the classical triphasic three-burst pattern is applicable for describing the activation patterns from all segments of three large radiate muscles. This aim will be fulfilled by analysing the burst morphology of each segment to determine if each agonist and antagonist segment exhibit typical EMG patterns as predicted by previous literature[3] on the triphasic EMG burst pattern.

Materials and Methods

Subjects

Sixteen neurologically healthy male volunteers, with no previous history of shoulder injuries, participated in this experiment. The subject's ages ranged between 18 and 30 years (mean age 22 ± 3.1yrs) with anthropometric characteristics indicating predominantly lean muscular physiques with bodyfat levels below 16 percent[7].

Protocol

Subjects performed a series of rapid (< 400 msec) dynamic shoulder joint adduction movements against the resistance of a free weight pulley and cable apparatus (Figure 1) whilst seated upright in an experimental chair. Specifically, subjects were seated with their upper limb abducted to 90° in the coronal plane (starting position) with their forearm resting on a triangular padded cable handle situated 50 mm distal to the elbow joint (Figure 1). This positioning helped alleviate excessive valgus forces that would have been felt at the elbow joint had the cable handle been grasped in the palm of the hand. No muscular activity was necessary to maintain this abducted position. This was verified by baseline EMG data from all segments at rest. The angular distance of the movements was kept constant in all trials, being equal to 40°. The subjects completed the trials with the aid of feedback from a storage oscilloscope.

Prior to the recorded trials, subjects were given 30 practice trials during which they were encouraged to move "as fast and accurately as possible" over the 40° angular movement distance. Subjects were instructed to move from their initial arm position to the final arm position according to the limits displayed on a storage oscilloscope. This was to be performed approximately 1000 ms after a verbal trigger signal. The subjects were then to hold the final position for a further 500 ms and then return the load slowly to the initial position and wait for the next signal. A total of 10 trials were recorded for data analysis. Inter-trial intervals were approximately 20 seconds in duration.

Equipment

A series of pulleys and cables loaded with free weights provided the external resistance. The load utilised during this experiment was a medium weight of 9.2 kg, with this figure being derived solely from the free weights utilised. This weight provided enough of a load to support the arm whilst not being so heavy that the movement could not be performed fast enough to obtain a triphasic EMG burst pattern.

A digital computer recorded shoulder joint angles from the electrogoniometer and muscle EMG's were sampled at 2000 Hz over a recording period of 2000 ms. Shoulder joint angle was measured by a 10 turn, 20 K electrogoniometer with its shaft attached through the centre of a V pulley. Velocity and acceleration were measured off line by double differentiation of the electrogoniometer trace. This was made possible with prior experimentation utilising a Cathode Ray Oscilloscope, custom arthrodial protractor and the electrogoniometer, which found that 1°, was equal to 44 millivolts.

Electrode Sites

Electromyographic activity from six sites of pectoralis major, all sites of the latissimus dorsi except L4 (five sites total), and segments D1, D3, D5 and D7 of the deltoid were utilised for recording purposes (for explanation of recording sites see[15,16]). The peripheral segments of each muscle were always included and it was decided that recording from only 4 segments of the deltoid would be more than adequate. Segment L4 was the chosen segment for exclusion along with D2, D4 and D6 also excluded due to the limitation of only 15 EMG channels available.

EMG Analysis

Raw EMG signals, representing muscle activity from the adduction task, were rectified and low-pass filtered (fifth order Butterworth filter) at 20 Hz to allow for temporal variables (segment onset, peak and offset) to be identified. These temporal variables were determined by visual inspection and with the aid of a threshold detector set at 10% of maximum amplitude. The onset of the electrogoniometer trace was also taken to be at 10% of the maximum amplitude. The analysis of these temporal variables thus enabled the detection of differences in the activation patterns (eg, onset and duration) of each segment waveform.

The shapes of the EMG bursts representing the activation of each segment were categorised in this experiment and from preliminary data it was envisaged that four types of EMG waveforms would become apparent. These hypothesised types of agonist and antagonist EMG waveforms were as follows:

- One burst pattern.
- One continuous burst pattern.
- Two continuous burst pattern.
- Two non-continuous burst pattern.

A summary of the hypothesised temporal activation patterns for the four types of EMG bursts to be analysed is categorised below in Table 1.

The differentiation between a one-burst pattern and a one-continuous burst pattern of EMG activity will be considered to be a duration, which represents the majority of the movement time (250 ms). This is in accordance to earlier research[4], which found that fast ballistic movements (similar in degrees to our experiments) result in EMG bursts of less than 250ms in duration. For example, EMG burst duration's less than 250 ms will be considered as being one-burst, and EMG burst duration's >250 ms being considered as one-continuous burst. The differentiation between a one-continuous and a two-continuous burst pattern was by visual inspection with any indication of two bursts being given a two-continuous burst criterion. For segments EMG to be considered two-non-continuous bursts the amplitude within the silent period between the two bursts had to be below 10% of the peak intensity. The classification between two-continuous and two non-continuous bursts was considered valid as agonist segments typically display a relative silent period between the first (Ag1) and second (Ag2) bursts[3]. When a segment displayed a two-burst pattern, the onset and offset of each burst were determined whilst only the largest peak amplitude, in whichever burst it appeared, was stored. The segmental EMG bursts from within each trial were categorised using both the raw and the linear envelope signal. The existence of significantly ($p<0.05$) different types of EMG waveforms between segments (according to the previously mentioned criteria) was taken to be suggestive of functional differentiation within the muscle.

One-Way Repeated Measures ANOVAs were used to determine differences in type of burst patterns and onset times amongst segments. A Student-Newman-Keuls test was used for post-hoc comparisons of significant ($p<0.05$) differences.

Results

Overall summaries of the results for the dynamic adduction task are displayed below in Table 2. This table depicts the functional roles adopted by segments during the adduction movement. Note that the functional roles of segments have been extended to include two types of antagonists (primary and secondary) due to significant ($p<0.05$) differences between antagonist segments. A late activation and predominant one burst pattern were used to characterise a primary antagonist segment, whilst an earlier activation and a less predominant one burst pattern were used to characterise a secondary antagonist segment (See Table 2 for more details).

Burst Morphology

The EMG morphology analysis revealed four types of EMG bursts (Figure 2) as predicted and outlined in the methods section. The four types included:

- One burst patterns.
- One continuous burst patterns.
- Two continuous burst patterns.
- Two non-continuous burst patterns.

Figure 3 illustrates a representative raw EMG trace from a single trial during the adduction task for an overview of the data.

For the pectoralis major, a trend was apparent where a two non-continuous EMG burst pattern was characteristic of the lower segments (P5 and P6 at over 80%) of this muscle (Figure 4). For example, significant ($p<0.05$) differences were apparent between the upper segments P1 and P2 (a lower percentage of a two non-continuous burst type) and P6.

Segments P1 and P2 also displayed a higher percentage of a One Burst pattern (39.4 ± 33.2% and 47.1 ± 38.7% respectively) when compared to P6 at 8 ± 9.8%.

For the latissimus dorsi a similar pattern to the pectoralis major was apparent where a two non-continuous EMG burst pattern was predominantly (>90 percent) exhibited from the lower segments (L3, L5, L6) of this muscle (Figure 5). Significant ($p<0.05$) differences in a two non-continuous burst pattern were evident between the upper segment L1 (50.9% +-26.6) in comparison to L6 (97.5% +-6.8). Significant ($p<0.05$) differences between the remaining segments and L6 were not apparent.

Of the three muscles analysed the deltoid displayed the greater number of significant ($p<0.05$) differences in the type of EMG waveform detected within its constituent segments (Table 3 and Figure 6). For example, D3 exhibited a significantly ($p<0.05$) larger percentage of a one burst EMG pattern (97.3% of the time) in comparison to all other segments during the adduction dynamic task with D1 at 44.9% being the next highest percentage of a one burst EMG pattern. A one-continuous burst pattern was predominantly displayed by D5 and D7 with significantly ($p<0.05$) higher percentages displayed when compared to D3 (Table 3).

Temporal Analysis

Figure 7 gives an overall impression of segmental activation during the adduction dynamic task showing that all segments from all muscles tested were activated (>10% MVC). A trend was apparent where the lowermost segments (L6 and P6) of the latissimus dorsi and the pectoralis major were activated first with the wave of myoelectric activity spreading superiorly to sequentially activate the more superior segments of these muscles. The middle segment of the deltoid (D3) was the last to be activated. Note the temporal delays between the agonist (all pectoralis major and latissimus dorsi and segment D7) and antagonist (D3, D5 and D1) segments.

Discussion

The triphasic EMG pattern is well documented in representing a basic neuromotor control strategy for rapid limb movements[1, 2,8,10,13] less than 400 ms[5]. It is characterised by two bursts from the agonist muscle/s that are separated by a silent period, and a one burst pattern at some point inbetween these two bursts from the antagonist. To date experimenters have utilised one, or possibly two, agonists or antagonist electrode sites to investigate the triphasic EMG pattern. The possibility of distinct differences in the EMG waveform patterns when recording from multiple agonist/antagonist electrode sites across the breadth of large radiate muscles, as determined in this experiment, have not previously been considered.

From the results it was apparent that the EMG waveforms associated with the triphasic EMG burst pattern[•] were not homogenously displayed across the breadth of the three muscles. Specifically, the expected waveforms were predominantly displayed by segments of the muscles that have been labelled as the prime mover and what has been termed the primary antagonist segments. The basis for this labelling of segment function being that a high percentage of a two non-continuous EMG burst type was taken to be indicative of prime mover segment function, whilst a one burst pattern is predominantly exhibited by agonist (prime mover) muscles during fast dynamic movements[1,2,3]. Instead of these *two* characteristic burst patterns, what was apparent, however, was the presence of *four* types of EMG waveforms (one burst, one continuous burst, two continuous bursts and a two non-continuous burst pattern) distributed amongst segments. It is thus the author's opinion that,

[•] Typically a two non-continuous burst pattern for the agonist and a one burst pattern for the antagonist.

with the variety of different EMG waveforms displayed in this current work, the classically described triphasic EMG burst pattern is not appropriate for a description of segment activation patterns across the breadth of large radiate agonist and antagonist muscles; such as the muscles investigated in this experiment.

A further finding in regard to the triphasic EMG burst was the later onsets of the primary antagonist segment/s in relation to the secondary antagonist segment/s (Figure 7). This is in direct contrast to the prime mover segments of the pectoralis major and latissimus dorsi during adduction, which were categorised partly because of their early onsets. An explanation for this finding may stem from differences in reciprocal innervation amongst the antagonist segments of the deltoid. It is well known that reciprocal innervation of agonist and antagonist muscle groups occurs during movement. The results of the current work would suggest that certain portions of an antagonist muscle (primary antagonist segments) receive a 'stronger' neural inhibition which results in the onset's of these segments being significantly ($p<0.05$) delayed in comparison to other antagonist segments of the same muscle.

The functional roles of deltoid segments are indicated in Table 2. This table shows that the segments of the deltoid assumed both synergistic (D7) and antagonistic (D1, D3 and D5) roles during the adduction motion. This is exemplified, in part, by the onset times displayed in Figure 7. For example, the relatively early onset time of segment D7 (in comparison to the other deltoid segments) indicated its lack of involvement as an antagonist segment. The onset time of D7 was found to be significantly ($p<0.05$) earlier than D5 thus categorising D7 as a synergist segment to aid the latissimus dorsi and pectoralis major segments in producing the initial EMG burst. In contrast, the significant ($p<0.05$) temporal delays between D1, D3 and D5, in comparison to all other active segments indicated their involvement in the antagonist (Ant) burst (second part of the classical triphasic burst pattern) confirming their antagonistic roles. Therefore, in comparison to the pectoralis major and the latissimus dorsi, whose segments functioned as prime movers and synergists, deltoid segments functioned as synergists, primary antagonists and secondary antagonist segments (Table 2) during the unperturbed adduction dynamic task. For example, of the three antagonist segments, Table 2 shows that only segment D3 was designated as the primary antagonist segment during the adduction task. This was due to a significantly ($p<0.05$) later onset and its total lack of a second EMG burst. Furthermore, D3 exhibited a significantly larger percentage of a one burst EMG pattern (97.3% of the time) than all other segments during the adduction task with D1 at 44.9 % being the next highest percentage of a one burst pattern. A one continuous burst pattern was predominantly displayed by D5 and D7 with significantly ($p<0.05$) higher percentages displayed when compared to D3 (Table 2). The categorisation of these two types of antagonist segments from the deltoid mass seemed warranted with the differences in onsets and burst patterns apparent amongst segments D1, D3 and D5 in the braking of the adduction movement.

In conclusion the triphasic EMG burst pattern could not account for the activation patterns of all segments across the breadth of these multisegmental muscles. This was particularly apparent with the novel finding of four different types of EMG waveform patterns and the differences in antagonist activation patterns, which gave rise to the classification of two types of antagonist segments. If agonists can have two subcategories (prime movers and synergists) why not antagonists? To further extrapolate, the results also suggest that caution is warranted if stating that popular motor control theories[10,11], based on EMG patterns produced by small agonist and antagonist muscles during rapid limb movement, apply to all segments of large radiate muscles. Further research is needed to validate this statement.

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Table 1. EMG burst categorisation. See text for more details.

One Burst Pattern	= <250 ms in duration
One Continuous Burst Pattern	= >250 ms in duration
Two Continuous Burst Pattern	= Two bursts joined (no silent period)
Two Non-continuous Burst Pattern	= Two bursts separated (silent period)

Table 2. The functional roles adopted by each segment during the adduction task. Note that the functional roles relate to the movement and not for each individual muscle for simplicity reasons. Prime mover segments were characterised by early onsets and a high percentage of a two non-continuous burst pattern. To distinguish between these segments and synergist segments, which are characterised as having slightly later onsets and a lower percentage of a two non-continuous burst pattern, the synergist segments needed to display at least one significant ($p<0.05$) difference in these dependent variables to a prime mover segment. For the multiple prime mover segments there was no significant differences displayed in any dependent variable for these segments. Segments that display at least one significant ($p<0.05$) difference to *any* of the designated prime mover segment/s were labelled as synergists. The antagonists were denoted by their later onsets and one burst patterns. Significant ($p<0.05$) differences were found amongst the antagonist segments in onset times and burst patterns (see results).

Movement	**Prime Movers**	**Synergists**	**Primary Antagonist**	**Secondary Antagonists**
Adduction	L2, L3, L5, L6 P5, P6	L1, P1, P2, P3, P4	D3	D1, D5

Table 3. EMG burst categorisation table delineating quantitatively the type of EMG burst most representative for segments of the deltoid during the adduction task. A (*) is used to indicate significant ($p<0.05$) differences between that segment and D3. Standard deviations are in brackets. Grand mean data from 16 subjects.

	One Burst (%)	One Continuous Burst (%)	Two Continuous Bursts (%)	Two Non-Continuous Bursts (%)
D1	44.9* (42.1)	23 (31.1)	9.6 (16.4)	21.8* (35.3)
D3	97.3 (10.0)	2.5 (10.1)	0 (0)	0 (0)
D5	39.1* (32.5)	55.1* (29.0)	.5 (3.1)	6.1 (23.4)
D7	4.7* (12.6)	53.1* (37.0)	14.7* (17.8)	27.5* (22.7)

Figure 1. The experimental set-up.

Figure 2. Representative EMG burst pattern types for the adduction task. Four different types of bursts were identified (see methods). A One Burst criterion was characteristic of D3 whilst a Two Non-continuous Burst criterion was characteristic of L6. Representative EMG data from various subjects.

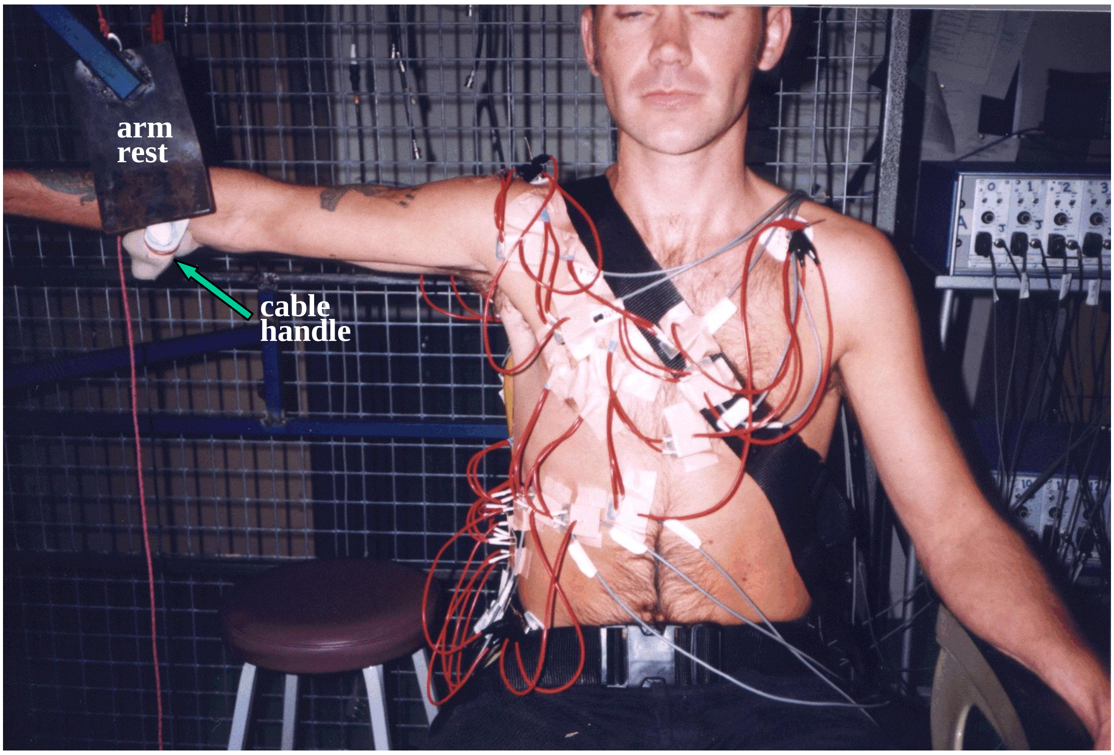
Figure 3. Raw EMG traces for a single trial from one subject during the adduction task. Selected segments have been expanded (right side) to emphasise the four different types of EMG burst patterns, which were the most commonly seen from these selected segments

Figure 4. A schematic diagram illustrating the predominant type of EMG burst that was apparent for that particular segment during the adduction task. Note that all segments except P2 predominantly displayed a two non-continuous burst pattern with a gradual decrease in this two non-continuous burst pattern from P6 to P1. Also note that P1 is the most superior segment with P6 the most inferior. Grand mean data from 16 subjects.

Figure 5. A schematic diagram illustrating the predominant type of EMG burst that was apparent for that particular segment. Note that all segments predominantly displayed a two non-continuous burst pattern with a gradual decrease in this two non-continuous burst pattern from L6 to L1. Note that L1 is the most superior segment and L6 the most inferior. Grand mean data from 16 subjects.

Figure 6. A schematic diagram illustrating the predominant type of EMG burst that was apparent for that particular deltoid segment. The deltoid has been oriented vertically to coincide somewhat with its anatomy as seen from a lateral view of the right shoulder. D1 is the most anterior segment with D7 being the most posterior. See Table 6 for more quantitative measures. Grand mean data from 16 subjects.

Figure 7. Onset times (ms) for segments during the adduction task. Segments activated before the onset of the force (0 ms to the left) are given negative values with segments activated after the force record (0 ms to the right) given positive values. Segments have been graphed according to anatomy starting anteriorly from the lowermost pectoralis major segment (P6), to ascend superiorly over the shoulder to then descend to the most inferior latissimus dorsi segment (L6). Note the waves of activation (represented by dotted lines), both anteriorly and posteriorly, meeting at the D3 segment. Standard error bars are shown with this graph representing grand mean data from 16 subjects.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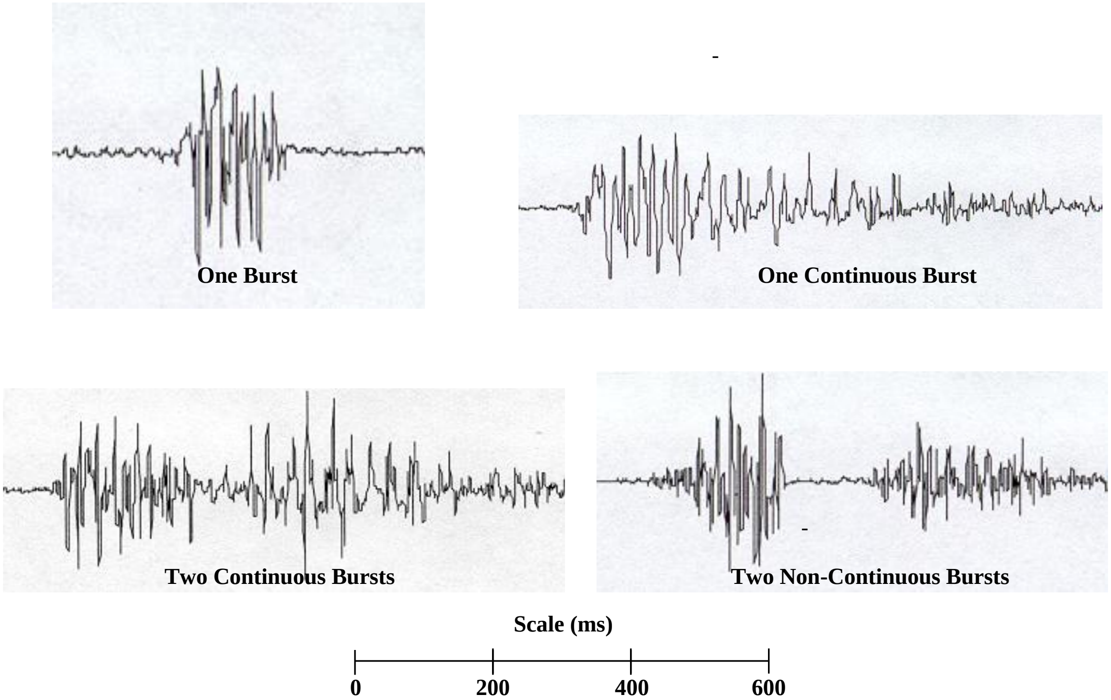
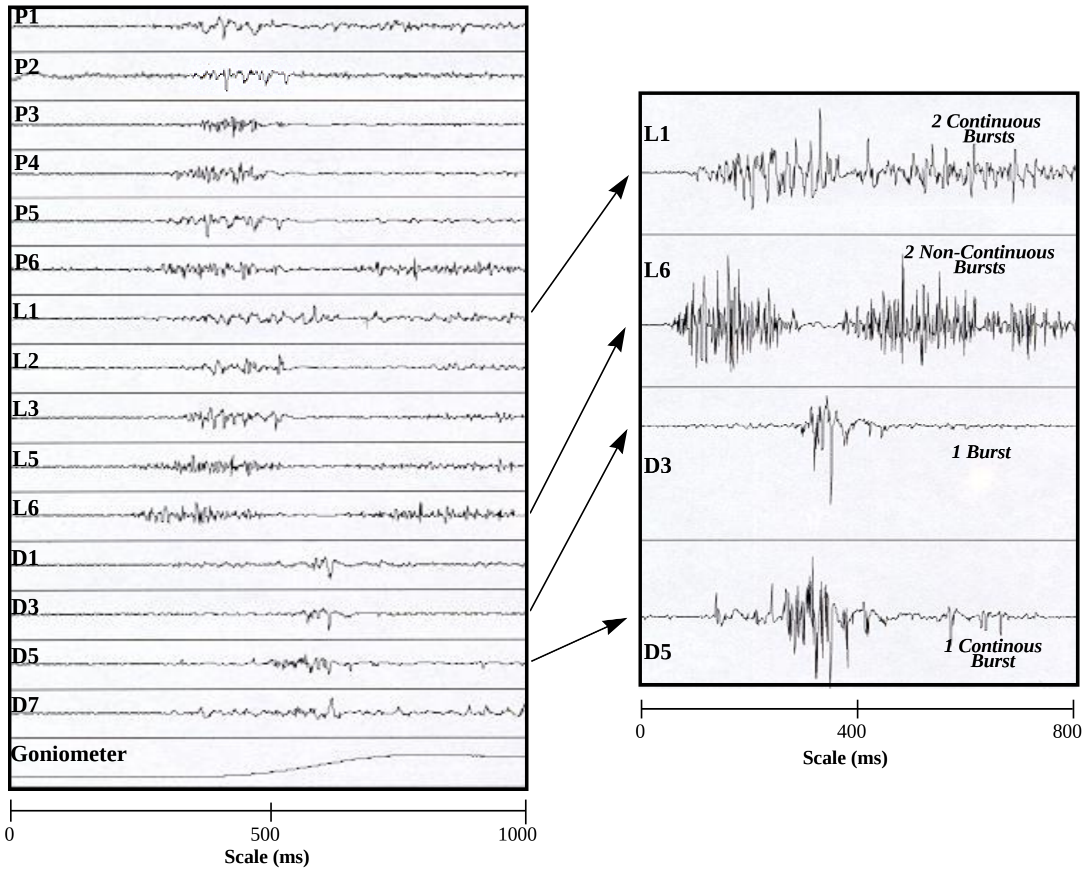
rest
cable
handle


One Burst
One Continuous Burst
Two Continuous Bursts
Two Non-Continuous Bursts
Scale (ms)
0
200
400
600


P1
P2
P3
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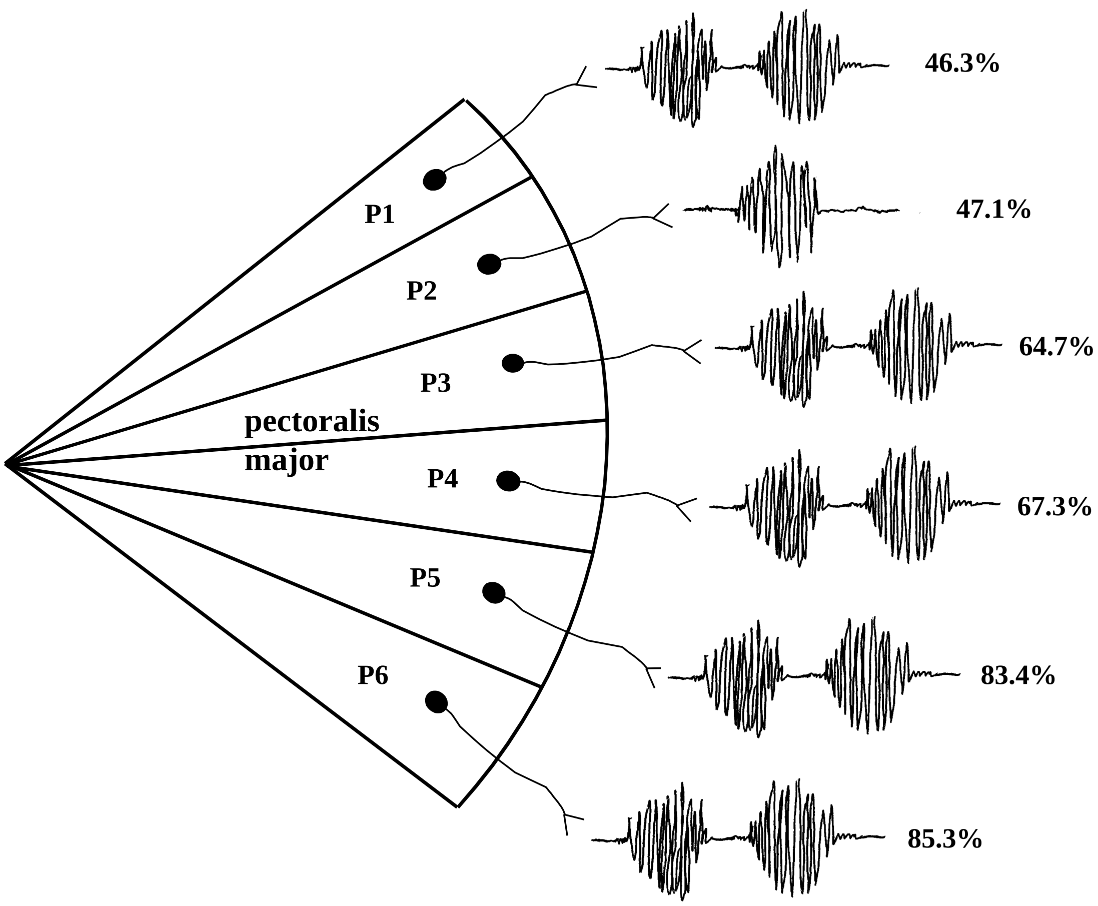
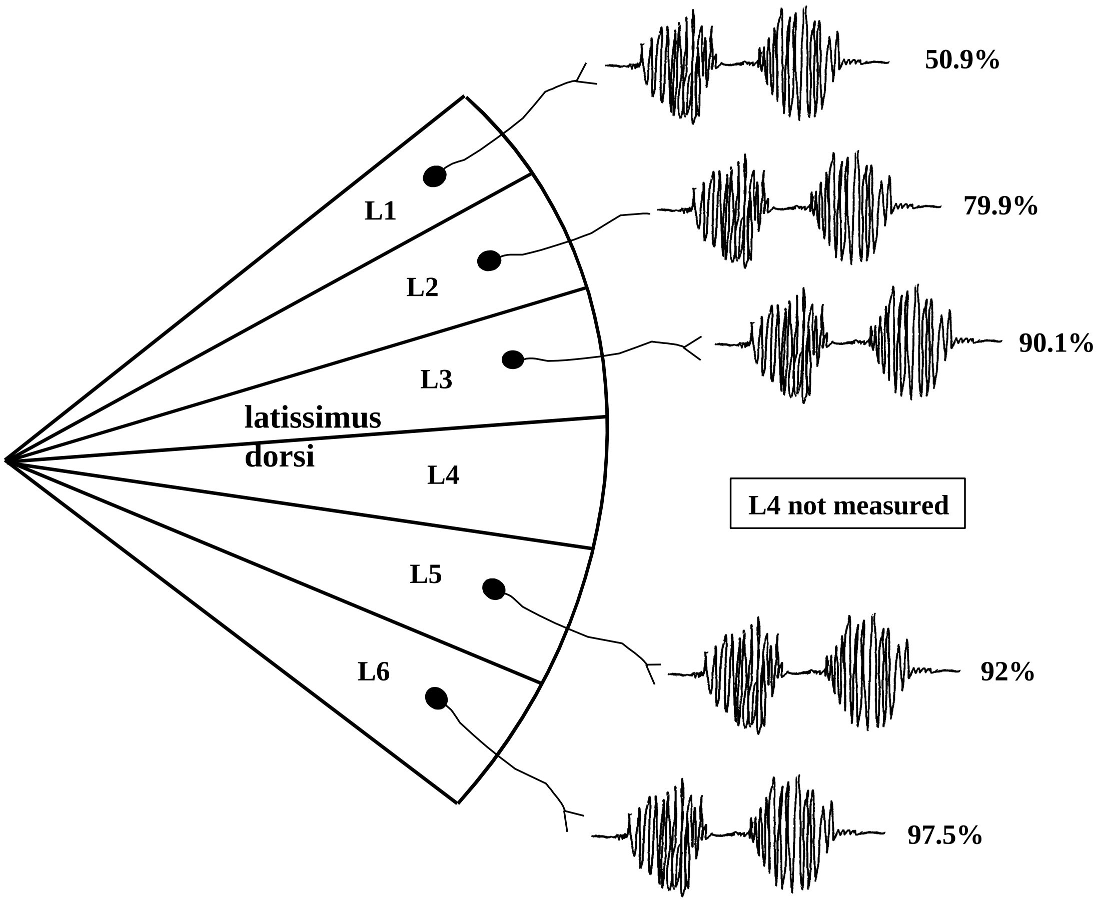
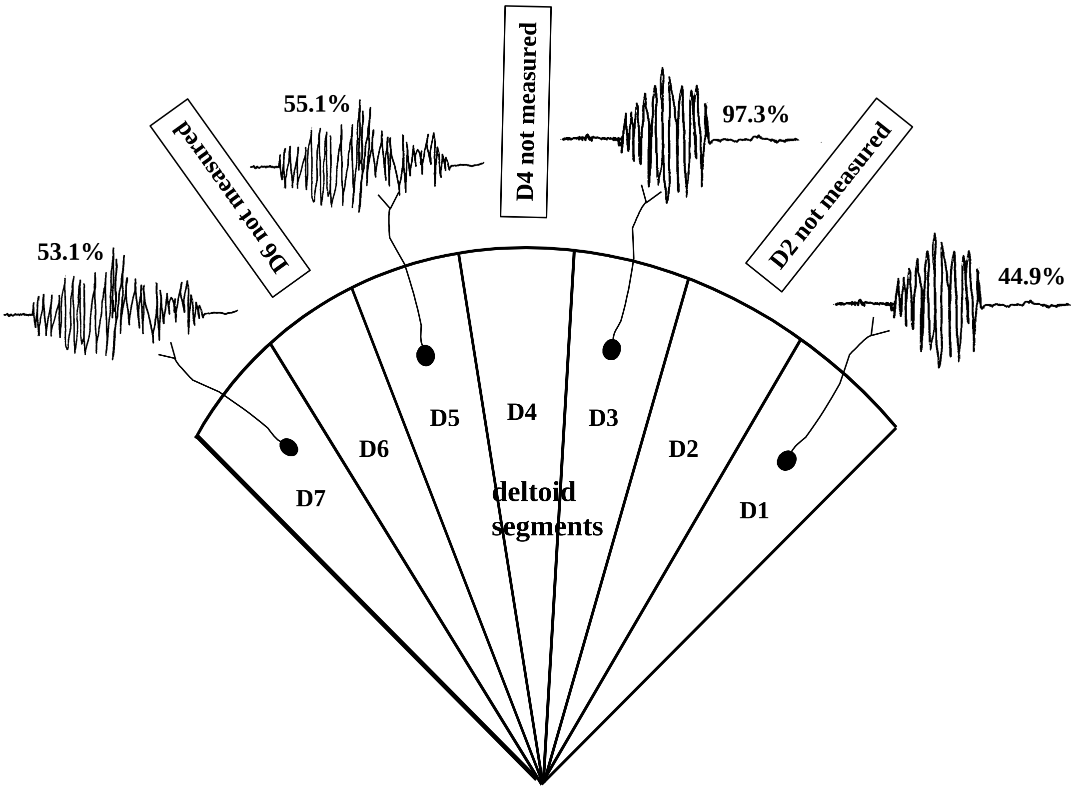
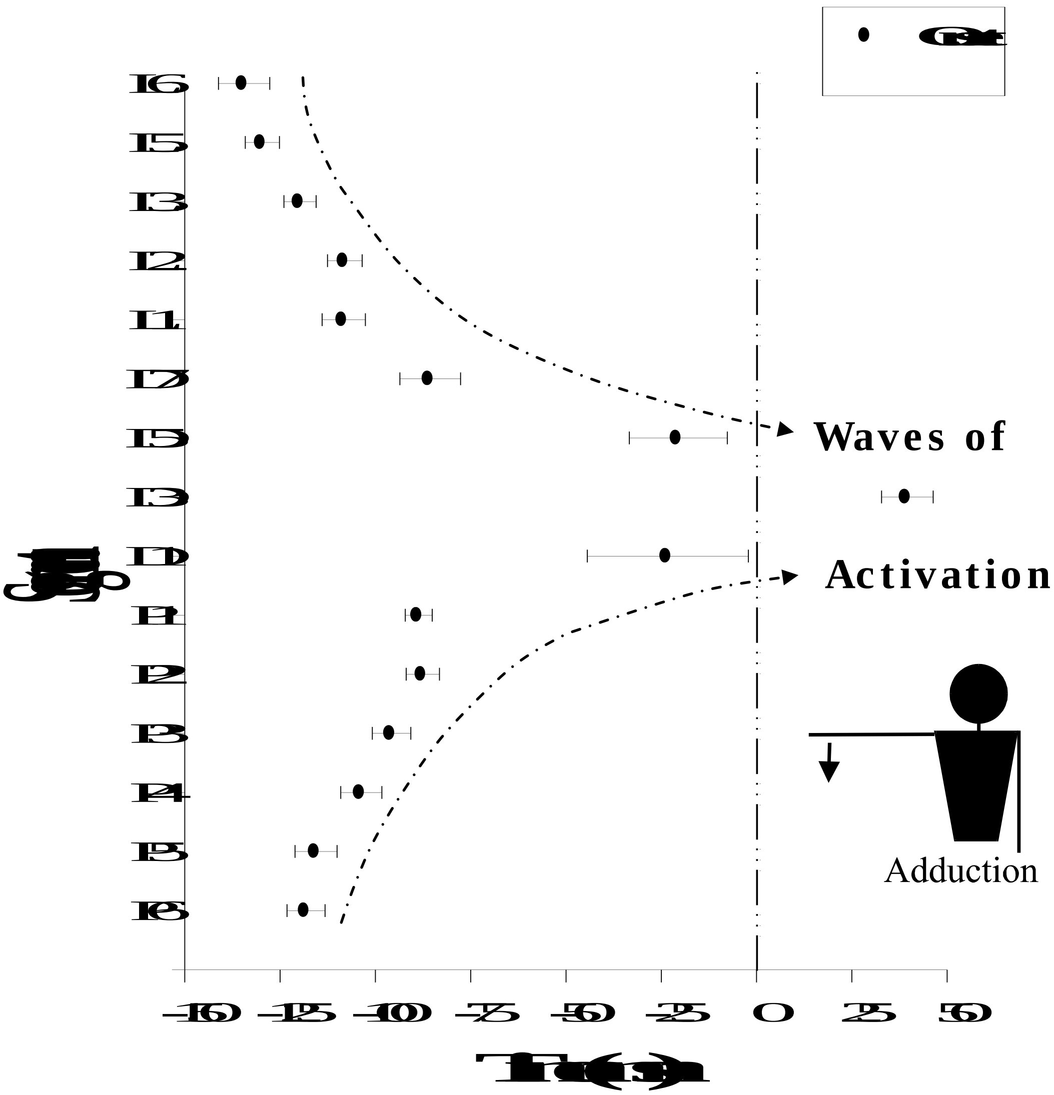
P6
L1
L2
L3
L5
L6
D1
D3
D5
D7
Goniometer
0
500
1000
Scale (ms)
L1
2 Continuous Bursts
L6
2 Non-Continuous Bursts
D3
1 Burst
D5
1 Continous Burst
0
400
800
Scale (ms)


46.3%
P1
47.1%
P2
64.7%
P3
pectoralis
major
P4
67.3%
P5
P6
83.4%
85.3%


50.9%
79.9%
90.1%
L1
L2
L3
latissimus
dorsi
L4
L4 not measured
L5
L6
92%
97.5%


55.1%
D4 not measured
97.3%
D6 not measured
D2 not measured
53.1%
44.9%
D7
D6
D5
D4
D3
D2
D1
deltoid
segments


Waves of
Activation
Adduction