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Abstract: The objectives of this study were two-fold. Firstly we wished to investigate the segmental anatomy, geometry and gross innervation patterns of selected shoulder joint musculature (pectoralis major, latissimus dorsi and deltoid) to establish if these muscles could be anatomically subdivided according to predetermined criteria. We then wished to use this information to help determine if a segments activation pattern was reliant on an efficient line of action and a large moment arm for the intended movement. Surface electromyography was used for this purpose whilst manipulating the independent variable of contraction intensity (% MVC) during two shoulder joint flexion tasks. For the anatomical portion of the study the dissection of ten cadaveric shoulders revealed the deltoid to consist of seven segments whilst the pectoralis major and the latissimus dorsi were both ascribed six segments according to predetermined anatomical/functional criteria. Primary nerve branching was evident in each muscle but no apparent relationship existed between the designated anatomical segments and the primary nerve branches. Differences were evident in the geometry of each segment in regard to moment arms and orientations of each segments line of action. The functional portion of this study, which utilized miniature bipolar surface electrodes during the performance of a static shoulder joint flexion task at 75% and 25% MVC, showed significant differences (p<0.05) in the activation patterns of active segments between the two tasks. Specifically, a "drop out" of segments with smaller flexion moment arms and more diverging lines of action in comparison to the movement plane was evident for all subjects in the 25% MVC task in comparison to the 75% MVC task.

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Muscles within Muscles: Anatomical and Functional Segmentation of Selected Shoulder Joint Musculature

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Summary

The objectives of this study were twofold. Firstly we wished to investigate the segmental anatomy, geometry and gross innervation patterns of selected shoulder joint musculature (pectoralis major, latissimus dorsi and deltoid) to establish if these muscles could be anatomically subdivided according to predetermined criteria. We then wished to use this information to help determine if a segments activation pattern was reliant on an efficient line of action and a large moment arm for the intended movement. Surface electromyography was used for this purpose whilst manipulating the independent variable of contraction intensity (%MVC) during two shoulder joint flexion tasks.

For the anatomical portion of the study the dissection of ten cadaveric shoulders revealed the deltoid to consist of seven segments whilst the pectoralis major and the latissimus dorsi were both ascribed six segments according to predetermined anatomical/functional criteria. Primary nerve branching was evident in each muscle but no apparent relationship existed between the designated anatomical segments and the primary nerve branches. Differences were evident in the geometry of each segment in regard to moment arms and orientations of each segments line of action.

The functional portion of this study, which utilised miniature bipolar surface electrodes during the performance of a static shoulder joint flexion task at 75 and 25% MVC, showed significant differences ($p<0.05$) in the activation patterns of active segments between the two tasks. Specifically, a ‘drop out’ of segments with smaller flexion moment arms and more diverging lines of action in comparison to the movement plane was evident in the 25% MVC task in comparison to the 75% MVC task.

Introduction

Skeletal muscles have traditionally been categorised by major anatomical subdivisions characterised on the basis of fascial sheets, major nerves and points of attachment; this classification being derived from a purely anatomical viewpoint. This categorisation of muscle tissue is more than acceptable at initially defining what a muscle is anatomically, but may be too simplistic to describe what a muscle does functionally. For instance, a muscle's action can be reasonably determined by its relative position at a joint/s. However, it cannot be assumed that the whole muscle will be activated homogenously to produce the supposed joint action. This is particularly apparent for large radiate muscles, as the moment arm and the resulting line of action for some segments of these muscles may be inefficient to produce the desired joint movement due to differences in segmental geometry across the breadth of the muscle. Furthermore, these differences in geometry amongst segments of a muscle may also be coupled with discrete primary nerve branching to these identified segments, which could potentially enable independent activation of segments. Detailed anatomical/neurological [1,4-6,15] and geometrical analyses [12] have been performed on muscle structure to elucidate, in more detail, the actual role of each muscle. However, these above mentioned studies have usually only focused on one or two aspects of muscle design (anatomy and/or neural innervation patterns) without considering muscle geometry (eg, moment arms and lines of action) or have focused on muscle geometry without considering in detail the anatomical design or neural innervation patterns. This experiment will attempt an integrated approach to the study of muscle architecture by quantifying the segmental anatomy, neural innervation patterns and segmental geometry of pectoralis major, latissimus dorsi and deltoid by dissection and a novel Three-Dimensional musculo-skeletal geometrical analysis. It is expected that by determining the muscle fibre architecture, segmental geometry and innervation patterns a clearer indication of a muscle segments' role during functional tasks can become apparent, particularly when the resulting segmental EMG patterns display evidence of functional differentiation during such functional tasks.

Previous research has shown functional differentiation to be present within segments of single skeletal muscles. [2,3,9,14,16,19] This occurs when segment/s of a muscle exhibit an earlier onset, higher intensity of activation or some other measured difference in comparison to the remaining muscle segments during a particular motor task. [3,9,19]
The evidence of functional differentiation displayed by segments during these studies has been either within the one movement or when movement direction was changed. As a secondary aim of this study the evidence of functional differentiation when contraction intensity is altered for a particular force direction will be investigated. This will be achieved by performing static shoulder joint flexion tasks at two levels of contraction intensity (25 and 75% MVC) at 400 ms time to peak static force. It is hypothesised that there will be a "drop out" of segments with smaller moment arms and less efficient lines of action for the force direction as contraction intensity (% MVC) is reduced.

Methods

Anatomical Procedures

Ten perfused adult male cadaveric shoulders were utilised for the dissection with the right shoulder of <u>one</u> cadaver fully dissected and used for both the anatomical and musculo-skeletal geometrical analysis. The left shoulder of the same cadaver was also fully dissected for the neural innervation analysis. The nine other shoulders were superficially dissected and used for anatomical comparison.

The four criteria utilised to identify a muscle segment included:

1. Distinctive origins and/or insertions (the differing origins on each rib for the serratus anterior would be considered to fall under this category of segment classification).
2. Architectural differences within the muscle mass; eg, strap vs pennate fibred segments.
3. Intramuscular fascial thickenings; likened to intermuscular septa within the muscle mass (perimysial thickenings).

Then, if none of these anatomical criteria were satisfied, a fourth geometrical criterion was utilised:

4. > 10° differences between the middle of each adjacent segment line of action. Intramuscular line of action differences of 10° has been shown to cause differing mechanical actions on the arm. [19]

Neural Innervation Procedures

The left side of the cadaver was used to determine the neural innervation of all three muscles, and their segments, with the objective of determining whether individual primary nerve branches innervate individual segments. The findings were confirmed through dissection of a second cadaver. The nerve branching to the pectoralis major (medial and lateral pectoral nerves), latissimus dorsi (thoracodorsal nerve), and the deltoid (axillary nerve) were hence followed by blunt dissection into the respective muscle masses as far as the resolution of the dissection microscope (x5) would permit anatomical observation.

Segmental Geometry Procedures

Line of Action Model

A straight line of action model [7] was implemented to ensure that the origin and insertion point screws, which represented the middle of each segment's origin and insertion, also represented the line of action of each segment upon contraction. This involved securing string lines between the self tapping screws, and pulling taut the string whilst noting if any bony or soft tissue structures interfered with a straight line of action for each segment. This was done with the cadaveric shoulder stabilised at 20 and 50° of abduction in the coronal plane.

In instances where the taut string lines contacted surfaces (boney, muscular or ligamentous structures) between their attachments, the origin was moved to a suitable “pseudo” origin, and this new origin was marked. This ensured that a straight line of action model was not violated. These origins were taken as the last point of string contact between segmental origin and insertion points.

Three-Dimensional Musculoskeletal Geometric Analysis

Three-Dimensional Cartesian Coordinates for each segment were obtained by utilising a vertical milling machine and custom-made pointers (Figure 1). The custom-made pointers were fastened to the milling machine vice and a cadaveric fixture (Figure 1) was placed in front of the mill upon which the bisected (transverse section through the iliac crests) cadaver was mounted. The milling machine X (horizontal; side to side), Y (vertical) and Z (horizontal; in and out) mill slides, when coupled with the custom-made pointers (front and back) fastened to a machine vice and bolted square to the mill table axis, provided a Three-Dimensional Coordinate system (accurate to 0.01 mm) for attaining anatomical locations. For our purposes the origin (0, 0, 0) of this coordinate system was the jugular notch. The fixture, with the mounted cadaver, was positioned on the floor in front of the mill table at a distance so as to allow the measurement of all anatomical points (delineated by self-tapping screws; see line of action model above) by both front and back custom pointers. Once in an appropriate position, the cadaver was aligned according to the Y and Z-axes of the milling machine. For example, this was achieved by aligning each acromion process with the custom-made front pointer to the same coordinate as displayed on the digital readout for Y and Z dimensions. Changes in the height of the fixture were made possible by adjusting screws in the bottom of each leg. Once in position the fixture was not moved for the duration of the experiment. With the cadaver accurately positioned in front of the milling machine the right upper limb was positioned at 20° of abduction (from the vertical) in the coronal plane by a custom arthrodial protractor and a spirit level taped to the bottom of the protractor. In this position all anatomical coordinates were gathered by manipulating the position of the pointer's end with the three mill handles to the centre of each screw (which represented each origin and insertion point).

The axis of rotation for the shoulder joint was considered as a fixed centre of rotation located in the middle of the humeral head with this positioning being used in similar experiments. [7] This position most closely approximates the instantaneous centre of rotation for the shoulder joint. [11]

Variables that were analysed included:

- Segmental moment arms.
- Angles between adjacent segment lines of action.

For reliability estimates the measurement of coordinates for the biomechanical analysis was repeated on three other separate occasions.

Scaling and Normalisation

Critical X, Y and Z dimensions (shoulder acromial width, sternum length and anterior-posterior chest depth respectively) from the shoulder girdle of the cadaver were recorded.

These same dimensions were measured in the subjects that were later used in the electromyographic experiments. The differences in these critical measurements between the cadaver and the subjects were then used as the scaling factor that was multiplied to each X, Y and Z coordinate from the cadaver.

Functional Procedures

Subjects

Twenty male volunteers, ranging between 18-30yrs (mean age 22 ± 3.1yrs) were recruited from a university population for this experiment. All subjects were right hand dominant and had no previous history of shoulder injuries or neurological disorders.

Protocol

Nineteen-miniature bipolar gold surface electrodes (6.5 mm inter-electrode distance; 1.6 mm active plates) were applied to the appropriate positions (according to the anatomical dissection) on the skin for each muscle segment. Subjects were then seated in an experimental chair with the upper limb fitted in an aluminium arm cast positioned so as the middle of the cast was at the level of the elbow joint. (Figure 2). With the upper limb abducted 20° in the coronal plane subjects were required to perform 10 static shoulder joint flexion tasks at 25 and 75% MVC at a movement time of 400 ms to peak and with an inter-trial interval of 30 seconds. Subjects were required to match a computer generated force-time curve on an oscilloscope, which provided the subject with feedback on direction, speed and force of contraction. Two load cells (a prime and an error load cell) secured to the arm cast and a wire cage at 90° to each other recorded the force of flexion contractions (prime) and any force in another direction (error load cell). Any trials registering a force on the error load cell were discarded. To permit normalisation of the intensity data, three MVC contractions were recorded for the flexion tasks (at the same position; 20° abduction in the frontal plane) at an inter-trial interval of three minutes between maximal contractions.

Electrode Sites

Illustrations for the normalisation of each electrode placement are depicted in Figure 3. For the pectoralis major, a solder wire (1 mm diameter) was laid down on each subject from the acromio-clavicular joint to follow the muscles' clavicular, manubrial, sternal and costal origins to the lateral most fibres of the lower (P6) segment. This length designated 100%, with each segmental origin measured in a similar fashion and then expressed as a percentage of this figure. Electrodes were placed at 25% (from the sternal origin) of the distance along a straight line connecting the centre of the segment origin and insertion (Figure 3). The approximate surface location of the pectoralis major insertion was considered to be the anterior axillary crease.

A similar procedure was used for the deltoid. A solder wire was laid out on each subject starting from the sterno-clavicular joint, following the muscles' clavicular, acromial and spine of scapula origins, to terminate at the medial spine of scapula. This length again designated 100% with segmental origins measured in a similar fashion and then expressed as a percentage of this figure. The insertion of D3 was found by having the subject abduct his arm against resistance, which highlighted the terminal tapering of the deltoid muscle mass on the deltoid tuberosity. Segments D1 and D2 were designated as being 10 mm medial and 15 mm superior to this point whilst the D4 segment was located at 78% of the D3 insertion on the same line. The posterior segments were located 10-15 mm posterior to the D4 insertion point. Similarly, electrode sites were marked at 25% of the distance from the centre of the segment origin to its corresponding insertion. All details for the latissimus dorsi normalisation of electrode placement have been given in Figure 3.

Results

Anatomical Evaluation

Anatomy

Based on the previously described criteria, six segments (P1-P6, superior to inferior respectively) were identified for the pectoralis major with all segments being able to be distinguished on the basis of their divergent lines of action. Distinct attachment points or the presence of intramuscular fascial thickenings were only able to distinguish four of these segments (P1, P2, P5 and P6). For example, segment P2 was easily delineated from P1 and P3 by intramuscular fascial thickenings at its superior and inferior borders. Segment P5 had slips of its origin arising from muscle fibres of rectus abdominis whilst segment P6 had attachments onto the aponeurosis of the external oblique. Segments P3 and P4, both with a non-distinctive sternal origin, could only be distinguished by their divergent lines of action. A distinctive twisting of fibres near their insertion where the lower-most fibres inserted more superiorly and the upper-most fibres more inferiorly on the lateral lip of the bicipital groove was apparent.

Similar to the pectoralis major six segments were distinguished in the latissimus dorsi (L1-L6, superior to inferior respectively). One segment (L6) was able to be distinguished based on differences in its origin and/or insertion (lower three ribs), however, L1-L5 was only able to be distinguished by their differing lines of action. Only L6 could be definitively separated from the remaining latissimus dorsi muscle mass due to attachment differences as L6 had a costal attachment whereas L5 originated on the pelvis. Accordingly, similar to the segments of pectoralis major this area of the latissimus dorsi muscle mass was equispaced to allow for 5 segments (L1-L5) to be delineated. L1-L5 was therefore definitively categorised according to the geometrical criterion of a >10° difference in their lines of action between adjacent segments (Table 1). Only 6° were apparent between L5 and L6 (Table 1). Any more than these five equispaced segments would have resulted in line of action differences being less than 10° between adjacent segments.

The latissimus dorsi also exhibited similar insertional characteristics to the pectoralis major with a twisting of fibres onto the medial lip of the bicipital groove with differing insertion points for some segments.

Deltoid

The deltoid muscle was divided into seven segments based on architectural differences within the muscle mass and differing origin and insertions with line of action differences also apparent between segments. In contrast to the latissimus dorsi and the pectoralis major seven anatomically distinct segments were found and large sections of the muscle were not homogenous. Line of action differences were still evident between some adjacent segments (Table 1) but differing attachments now delineated the boundaries of each segment to a greater extent than in the previous two muscles.

The most anterior segment was labelled D1 through to the most posterior segment, which was labelled D7. This result validated previous anatomical segmentation work [19] on the deltoid muscle mass.

Neural Innervation

Pectoralis Major

The lateral and medial pectoral nerves innervated the pectoralis major. The medial pectoral nerve originated from the medial cord of the brachial plexus and passed inferiorly beneath the pectoralis minor muscle. It then pierced this muscle to innervate approximately the lower third of the pectoralis major. Specifically, branches entered segments P4, P5 and P6 approximately midway along these segments length. The lateral pectoral nerve, being somewhat larger than the medial pectoral nerve, arose from the lateral cord of the brachial plexus and travelled on the undersurface of the proximal portions of pectoralis major whereupon branches entered the muscle. Specifically, the lateral pectoral nerve was divided into two branches with the uppermost branch entering P1 and P2 and the lowermost branch entering P3 and P4. This branch also had a portion joining the medial pectoral nerve near its origin.

Latissimus Dorsi

The latissimus dorsi received its innervation via the thoracodorsal nerve. This nerve arose from the posterior cord of the brachial plexus and split into two main primary nerve branches upon entering the axillary portion of the muscle. The uppermost branch entered L1, L2 and L3 and was seen to split into 4 to 5 smaller branches nearer the axillary portion of these segments. The other primary nerve branch entered the lowermost segments (L4, L5 and L6) with smaller branches entering these segments at more varying lengths of each segment. One of these branches split from the main peripheral nerve approx 40 mm more proximal and was considered to be a third primary nerve branch. This branch entered L4 about halfway along its length and showed no evidence of further branching.

Deltoid

The deltoid muscle, which received its innervation via the axillary nerve, was seen to split near the middle of the deltoid muscle length into four primary nerve branches. The largest branch (in both diameter and length) entered the anterior segments D1 and D2 before splitting into 5 or 6 terminal branches. Another branch entered segments D3 and D4 and divided into 3-4 terminal branches. A further two branches, the most proximal on the axillary nerve, could be seen entering segments D5, D6 and D7. These branches were the smallest in diameter.

Segmental Geometry of all Muscles

Lines of Action and Moment Arms

Line of action overviews for differences between adjacent segments of all muscles is displayed in Table 1. As indicated most segments displayed a >10° difference in their lines of action when compared to its adjacent segment/s with the pectoralis major showing the greatest amount of differences between its adjacent segments.

Moment arm data for segments of all muscles is given in Table 2. The average segment moment arms in both the frontal and sagittal planes are depicted. The moment arms for the sagittal and frontal planes were taken from a lateral and anterior view respectively.
When observed in a lateral view all pectoralis major segments had a flexor moment whilst all latissimus dorsi segments had an extensor moment with the largest moment arm within the latissimus dorsi associated with the most superior segment (L1 with 59.7 mm). Segments D1, D2 and D3 had lines of action anterior to the axis of rotation (flexors) whilst D4, D5, D6 and D7 had lines of action posterior to the axis of rotation, hence an extensor function (Table 2).

Figure 4 shows representative segmental lines of action data from an anterior view at a humeral elevation of 20° of abduction for one subject. These same lines of action were also viewed superiorly and laterally for a perspective from each of the three cardinal planes. It should be noted that only one line from both the transverse and sagittal planes could be seen in Figure 4 because of the frontal plane view. All three connected points designating the frontal plane as a right-angled triangle are illustrated.

Functional Evaluation

Evidence of Functional Differentiation by Changing Contraction Intensity

A comparison of onset times and % MVC values between the two contraction intensities are presented in Figure 5 and Table 3. The onset times depicted in Figure 5 show that all pectoralis major segments were activated during the 75 % MVC flexion task, (> 10 % MVC), whereas during the 25 % MVC flexion task only segment P1 was activated at 16.9% MVC (Table 3). Segment P1 also displayed its peak intensity significantly ($p<0.05$) earlier in the 25 % MVC contraction when compared to the 75 % MVC flexion task (Table 3). For the latissimus dorsi, only the most superior segment, L1, was activated during the 75% MVC flexion task (Figure 5 and Table 3). In comparison, the 25% MVC flexion task did not activate segment L1, or any other of the latissimus dorsi segments. For the deltoid during the 75% MVC flexion task the anterior and middle deltoid segments, D1-D4, were activated above 10% MVC whereas during the 25 % MVC task only the most anterior segments, D1 and D2, were active. Table 3 also shows that segment D1 was activated significantly ($p<0.05$) earlier in the 25 % MVC mode when compared to a later activation during the 75 % MVC contraction mode.

Discussion

Anatomy

After dissection of the 10 cadaveric shoulder joints, **seven** anatomical segments were found within the deltoid muscle mass based solely upon anatomical correlates (criteria 1-3; see methods). This was in contrast to the pectoralis major with four segments (P1, P2, P5 and P6) and the latissimus dorsi (L6) with one segment whilst the remaining muscle masses of latissimus dorsi and pectoralis major could only be subdivided according to line of action differences (criterion 4). Although both the pectoralis major and latissimus dorsi had broad origins the demarcation of where one segment boundary finished and another started was difficult to identify. Specifically, for the latissimus dorsi, the wide area of origin spanning the lower thoracic and all lumbar vertebrae, the posterior iliac crest, sacrum and lower three ribs seemingly ensured that differing origins would be apparent for each segment. However, the delineation of where one segment's muscle mass finished and another started could not accurately be ascertained due to muscle mass (L1-L5) attaching onto the thoracolumbar fascia and then to the respective regions of vertebrae or pelvis. Hence, the non-anatomical criterion (criterion 4) was implemented with the justification being that the resulting differences in lines of a action (>10%) would be enough to potentially cause a differing action on the arm if these segments were activated independently. This assumption is substantiated by research showing that intramuscular line of action differences (>10°) cause differing mechanical actions on the arm. [9,10,19] Although the three muscles did show evidence of anatomical segmentation the results of the functional analysis (eg, differences in EMG waveforms between segments) showed that a peripheral anatomical segmentation need not be present in these muscles for them to exhibit a functional segmentation. This was highlighted by the fact that segments which were categorised by non-anatomical criteria (line of action differences) exhibited independent activation patterns. Thus homogenous sheets of muscle mass like that from the pectoralis major and most segments bar one from the latissimus dorsi could still be functionally differentiated.

Neural Innervation

The results showed no evidence that segments of the three muscles received their own exclusive individual primary nerve branch. This was not surprising as the variables predominantly used for segment classification (lines of action and attachment points) are unlikely to determine nervous pathways throughout a muscle. As this was apparent for all segments including the anatomically defined segments it could not be stated that the anatomical segmentation present (intramuscular fascial thickenings, architectural differences or attachment differences) came with a concomitant neural segmentation (an individual primary nerve branch to each segment). Of particular interest for the neural dissection was that the dual innervation from the medial and lateral pectoral nerves was consistent with previous anatomical observations.[8,17] For the latissimus dorsi, a modal number of three, the number of primary nerve branches found in this project, has also been shown for the number of primary branches of the thoracodorsal artery.[13] Considering that arterial and nervous pathways are known to follow each other in their course, the finding of similar nervous and arterial branches may have functional significance.

Geometry

The hypothesis of this experiment was that their will be a “drop out” of segments with smaller moment arms and less efficient lines of action for the force direction as contraction intensity is reduced. When viewing Table 2 and Figures 4 & 5 it is evident upon close inspection that segments needed to possess both a flexor moment arm and an efficient line of action in order to be recruited for both flexion tasks. For example, although segments P2, P3 and P4 had the largest flexor moment arms (53.3, 49.7 & 32.2 mm respectively) they were only recruited for the 75% MVC task. These three segments have the most transverse line of actions for the pectoralis major and hence a large component of their force would also contribute to an adduction movement as can be seen by their large adduction moment arms. The segments that were recruited for both flexion tasks (D1, D2 & P1) possessed flexor moment arms greater than 15 mm but also possessed reasonably vertical lines of action (Figure 4), which are conducive to producing a flexion movement. With a segment's line of action and moment arm being the predominant factor in determining its activation pattern it is evident that the central nervous system has an acute awareness of which segments are most appropriate to perform a particular task.

Some segments (L1 and D4) were recruited during the flexion 75% MVC task but actually possessed an extensor moment arm at 20° abduction. It would seem as if these segments are acting antagonistically and thereby playing some stabilising role. In regard to L1, it is interesting to note that this segment possessed the most transverse line of action of the latissimus dorsi muscle mass and it would hence seem that the most appropriate segment to stabilise the head of the humerus against the glenoid fossa has been selectively recruited from the latissimus dorsi muscle mass. It is hypothesised that this segment is helping to prevent any anterior translation of the humeral head.

Evidence of Functional Differentiation by Changing Contraction Intensity

The strategy used to determine whether contraction intensity would influence a segment's activation pattern was to replicate the same task at two different levels of muscle contraction intensity. The chosen static task for this purpose was static shoulder joint flexion at 20° of abduction with the muscle contraction levels set at either 25% MVC or 75% MVC. The justification for this criterion to identify functional differentiation was on the premise that if all segments of a muscle were considered to be as functionally important for a particular movement then all parts of that muscle would be activated at any % MVC of contraction. This did not occur for the flexion trials and hence functional differentiation was apparent within each of the three muscles. The results (Table 3 and Figure 5) indicated a selective dropout (<10% MVC) of segments when comparing the 75% MVC flexion task to the 25% MVC task with only those motor units from segments with the larger flexor moment arms and more efficient lines of action (D1, D2 & P1) still being recruited in the 25% MVC flexion task. These were considered to be the prime mover segments. Furthermore, segments with the highest contraction intensities from the 75% trials also displayed the highest contraction intensities during the 25% trials. To summarise the effects of contraction intensity on segmental activation, it would seem that at low contraction intensities only motor units from segments with the most efficient lines of action and relatively large flexor moment arms (prime mover segments) are recruited for the task. With increasing contraction intensities motor units from segments of muscles with more oblique lines of action to the task direction (synergist segments) are recruited to aid the prime mover segments in producing the desired outcome.

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Segments	Lines of action; degrees of difference between adjacent segments
P1-P2	22 (1)
P2-P3	20 (1)
P3-P4	16 (1)
P4-P5	21 (1)
P5-P6	15 (1)
L1-L2	11 (1)
L2-L3	11 (1)
L3-L4	15 (0)
L4-L5	12 (0)
L5-L6	6 (1)
D1-D2	16 (1)
D2-D3	7 (0)
D3-D4	22 (1)
D4-D5	10 (0)
D5-D6	2 (0)
D6-D7	10 (1)

Table 1. The degrees of difference between adjacent segment lines of action for each muscle. Angular measurements were taken from both lateral and anterior views depending on the orientation of the segmental line of action. Values are in degrees. Standard deviations are in brackets. Grand mean data from 20 subjects.

Segment	Moment arms at 20° abduction in a sagittal plane		Moment arms at 20° abduction in a frontal plane	
	flexor	extensor	abductor	adductor
P1	20.5 (1.8)			38.5 (3.3)
P2	53.3 (4.2)			56.4 (5.6)
P3	49.7 (4.1)			52.6 (5.1)
P4	32.2 (2.4)			55.6 (5.9)
P5	12.1 (1.1)			43.9 (2.1)
P6	6.1 (.7)			41.6 (1.4)
L1		59.7 (4.8)		57.3 (4.9)
L2		54.4 (4.2)		52.1 (4.8)
L3		48.5 (3.8)		45.9 (3.5)
L4		30.6 (2.5)		35.5 (2.2)
L5		20.9 (1.9)		30.8 (1.6)
L6		15.8 (1.5)		27.8 (1.1)
D1	17.7 (1.6)		2.0 (1.5)	
D2	23.7 (2.2)		17.5 (.3)	
D3	8.3 (.8)		35.4 (1.4)	
D4		35.5 (3.1)	30.1 (.7)	
D5		45.9 (3.8)	16.9 (.3)	
D6		50.4 (4.1)	8.2 (.3)	
D7		62.9 (5.9)		10.5 (1.2)

Table 2. Segmental moment arms at 20° of shoulder joint abduction in the frontal plane. The moment arm data is given in millimetres with segment actions also extrapolated and labelled as either shoulder joint flexors/extensors (anterior or posterior to the joint centre respectively) and/or abductors/adductors (supero-lateral or infero-medial to the joint centre respectively). The moment arm data has been determined from both frontal (abductor and adductor) and sagittal (flexor and extensor) plane views. Values are in millimetres. Standard deviations are in brackets. Grand mean data from 20 subjects.

	Onset (ms)		Peak (ms)		Off (ms)		Duration (ms)		% MVC	
	75%	25%	75%	25%	75%	25%	75%	25%	75%	25%
P1	-47 (26)	-52 (29.8)	-75 (34)	≠ -163 (49)	170 (61)	≠ 107 (40)	625 (123)	576 (77)	41.9 (21.5)	≠ 16.9 (10.2)
P2	-38 (32)	≠ ---- ---	-88 (49)	≠ ------ ------	133 (74)	≠ ------ ------	576 (136)	≠ ----- -----	32.8• (17)	≠ ----- -----
P3	-11• (37)	≠ ----- ------	-80 (52)	≠ ----- -----	148 (66)	≠ ----- ------	567 (99)	≠ ----- -----	24.4• (12.9)	≠ ---- -----
P4	4 • (32)	≠ ------ ------	-46 (41)	≠ ------ -----	164 (46)	≠ ----- -----	576 (82)	≠ ------ -----	26.9• (15.6)	≠ ---- -----
P5	-2 • (36)	≠ ----- ------	-59 (49)	≠ ----- -----	186 (42)	≠ ----- -----	602 (86)	≠ ------ -----	30.7• (18.5)	≠ ---- ----
P6	3 • (44)	≠ ----- ------	-53 (29)	≠ ------ ------	176 (47)	≠ ----- -----	596 (88)	≠ ------ -----	27.2• (16.2)	≠ ---- -----
L1	35♦ (20)	≠ ------ -----	-85 (20)	≠ ------ -----	58♦ (28)	≠ ----- -----	349♦ (43)	≠ ----- ------	10.7♦ (23.9)	≠ ---- ----
D1	-27 (23)	≠ -50 (19)	-70 (29)	-103* (52)	151 (54)	114 (47)	586 (126)	585 (84)	54.8 (23.6)	≠ 21.6 (11)
D2	-29 (23)	-29 (32)	-75 (33)	-132 (36)	151 (56)	119 (47)	594 (125)	564 (81)	54.6 (24.1)	≠ 22.4 (9.7)
D3	11* (28)	≠ ----- -----	-82 (38)	≠ ----- ------	163 (61)	≠ ----- -----	548 (130)	≠ ----- -----	44.4* (15.8)	≠ ----- -----
D4	28* (23)	≠ ----- -----	-65 (25)	≠ ------ ------	138 (44)	≠ ----- ----	513 (96)	≠ ----- -----	19.3* (15)	≠ ----- -----

Table 3. The effect of a change in contraction intensity utilising the static flexion 75% and 25% MVC tasks. Only segments that were active (>10% MVC) in either of these two tasks are shown. Instances where the contraction intensity significantly ($p<0.05$) influenced a segments activation pattern between the two tasks are denoted with a (≠). Additional within movement comparisons have also been included with the pectoralis major using a (•) to indicate significant ($p<0.05$) differences between that segment and P1. For the latissimus dorsi a (♦) is used to indicate significant ($p<0.05$) differences between that segment (L1) and D2 and a (*) is used for the deltoid to indicate significant ($p<0.05$) differences between that segment and D2. Standard deviations are shown in brackets. Grand mean data from 20 subjects.

Figure 1. Photograph depicting the vertical milling machine, custom-made pointers and cadaveric fixture used for obtaining Three-Dimensional Coordinates from segmental attachment points located on the cadaver. By positioning the cadaver on the fixture placed in front of the milling machine, and moving the mill slides (X, Y and Z), the pointers could gather Three-Dimensional Coordinates of origin and insertion locations relative to a position of origin; 0, 0, 0 (the jugular notch).

Figure 2. The experimental set-up for the functional analysis. Depicted is one of the subjects seated in the experimental chair with the arm cast set at 20 degrees of abduction in the frontal plane. In this position subjects performed the static tasks of shoulder joint flexion at 25 and 75% MVC.

Figure 3. Illustrations of the deltoid, latissimus dorsi and pectoralis major outlining the normalisation procedures for accurate electrode placements between subjects. For the deltoid and pectoralis major the dotted line represents the course of the solder wire, which measured the total normalisation length (see text for details). For the latissimus dorsi, linear measurements were utilised. For example, an initial line was marked connecting the uppermost posterior axillary fold and the spinous process of the eighth thoracic vertebrae. A second line was also marked which connected the axillary fold with the lateral-most fibres on the cadaveric iliac crest. A line connecting, at 85% of the first and 65% of the second line, was then marked on the cadaver. The latissimus dorsi segments, and subsequent electrode placements, could then be equally spaced along this arrow headed line. A further segment was located 15 mm lateral and at 50% of the distance between the line running from the axillary fold to the iliac crest (designated by circle). This location delineated the fibres attaching to the lower three ribs.

Figure 4. A diagrammatic representation of a Three-Dimensional image of segment lines of action represented two-dimensionally. The segmental lines of action are depicted from an anterior view with the arm abducted at 20° in the frontal plane (three points joined in the frontal plane for a right-angled triangle). Segments are labelled at their origin with the exception of D1 and D2, which have been labelled at their insertion on the medial side of the deltoid tuberosity. Superior and lateral views were also used for the calculation of geometrical (segmental lines of action) and biomechanical variables (segmental moment arms). Computer aided design software (AutoCAD) was utilised for these purposes. Representative data (AutoCAD) from one subject.

Figure 5. Onset times for segments during static shoulder joint flexion tasks performed at 75% (circles) and 25% MVC (triangles) at 20° of shoulder joint abduction in the frontal plane. The dashed line represents the onset of the force record (load cell) with segmental onset times to the left (negative) of this line being activated before the onset of the force record. Segments are aligned according to anatomical location starting from the inferior pectoralis major segments ascending over the shoulder to then descend to the latissimus dorsi segment (L1). Note that all segments of the pectoralis major, the four most anterior segments of deltoid and the one superior segment (L1) of the latissimus dorsi were activated during the 75% MVC contraction compared to only P1, D1 and D2 being activated (>10% MVC) during the 25% MVC contraction mode. Standard error bars are shown. Grand mean data from 20 subjects.

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Po-Quang Chen
Journal of Musculoskeletal Research

Dear Dr Chen,

Enclosed are 4 copies of a manuscript for your perusal and hopeful acceptance into the Journal of Musculoskeletal Research. The authors await your upcoming correspondence and would be honoured if accepted for publication into your journal.

Yours truly,

Dr James Baldwin Wickham