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A NON-INVASIVE ANALYSIS OF THE STRUCTURE AND FUNCTION OF HUMAN MULTI-SEGMENTAL MUSCLE

A thesis submitted in fulfilment of the

requirements for the award of the degree

DOCTOR OF PHILOSOPHY

from

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By

DARRYL JOHN MCANDREW *B.Sc. (UoW)*

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Certification

I, Darryl John McAndrew, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Health Sciences, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Darryl John McAndrew
15 December 2008

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Thesis Organisation

Chapter 1 provides a general introduction to the thesis and specifically states the research objectives.

Chapter 2 reviews the relevant literature, including an overview of muscle fibre types, spatial distribution and contractile physiology, evidence for functional differentiation and research that specifically investigated non-invasive measurements of contractile properties.

Chapter 3 details the techniques used to determine the Tensiometric, Mechanomyographic and Myoelectric measures of muscle performance.

Chapter 4 describes experiments that validated the Laser-MMG technique for the detection of changes in muscle contractile properties induced by physiological modulators of muscle performance (temperature and fatigue). Confirmation of the Laser-MMG technique to detect the contractile properties of multiple muscle segments contained within a single animal muscle is also contained within.

Chapter 5 describes two experiments that examined the contractile properties of muscle segments within human multi-segmental muscles, for the purpose of matching contractile properties to functional roles. This chapter has been published in the Journal of Musculoskeletal Research.

Chapter 6 describes an experiment that examined the neuromotor control of 14 superficial muscle segments surrounding the shoulder during movements at different speeds.

Chapter 7 provides a summary and synthesis of the results from the three experimental chapters and draws conclusions regarding the spatial distribution of muscle fibres within multi-segmental muscle and their neuromotor control based on the objectives outlined in Chapter 1. Recommendations for future research and acknowledgment of experimental limitations are also made.

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Abbreviations

Abbreviation	Term
Cm	centimetre
CNS	central nervous system
CSA	cross sectional area
ºC	degrees Celsius
Dur	electromyographic duration
Dur*N*%	normalised electromyographic duration
Dmax	maximum displacement
EMG	electromyography
Fall	maximal rate of relaxation
FcOn	force onset
FcOff	force offset
FcPk	force peak
FDT	force development time
FT	fibre type
iEMG*N*%	normalised integrated EMG
Int	electromyographic intensity
Kg	kilogram
kHz	kilohertz
MDL	muscle displacement laser
mm	millimetre
MMG	mechanomyography
ms	millisecond
MT	movement time
mv	millivolt
MVC	maximum voluntary contractions
On	electromyographic onset
On*N*	normalised electromyographic onset
Pk	electromyographic peak
Pk*N*	normalised electromyographic peak
Rise	maximal rate of contraction
Tc	contraction time
tc*N*	normalised contraction time
TEN	Tensiometry
Tmax	maximum Tension
Tr	relaxation time
tr*N*	normalised relaxation time
Ts	sustain time
ts*N*	normalised sustain duration

List of Publications

The publications listed below are associated with the research conducted as part of this thesis.

Published Articles

McAndrew, D.J., Gorelick, M. and Brown, J.M.M. (2006). Muscles within muscles: A mechanomyographic analysis of muscle segment contractile properties within human gluteus maximus. *Journal of Musculoskeletal Research* **10**(1): 23-35.

McAndrew, D.J., Rosser, N. and Brown, J.M.M. (2006). Mechanomyographic measures of muscle contractile properties are influenced by the duration of the stimulatory pulse. *Journal of Applied Research.* **6**(2): pp 142-152

Conference Proceedings

McAndrew, D.J. and Brown, J.M.M. (2004). Muscles within muscles, inter- and intra-muscle segment coordination. *Proceedings of the Australian Association of Exercise and Sports Science Inaugural Conference*, Brisbane, Australia.

McAndrew, D.J., Gorelick, M. and Brown, J.M.M. (2004). Muscle belly displacement as a measure of fatigue. *Proceedings of the Australian Association of Exercise and Sports Science Inaugural Conference*, Brisbane, Australia.

McAndrew, D.J., Rosser, N., Gorelick, M., Phillips, K. and Brown, J.M.M. (2005). Mechanomyography for non-invasive clinical diagnosis in musculoskeletal rehabilitation. *Proceedings of the 4th International Cyberspace Conference on Ergonomics*, Johannesburg, South Africa.

McAndrew, D.J., Gorelick, M. and Brown, J.M.M. (2006). Mechanomyography for clinical decision making in exercise physiology practice. *Proceedings of the Australian Association of Exercise and Sports Science Conference,* Sydney, Australia.

Abstract

The Central Nervous System (CNS) exerts extensive control over muscle activation in order to produce accurate voluntary movement, such as the complex movements of the human shoulder joint. Muscles surrounding multi-planar joints are selectively activated depending upon the movement performed, and within the radiate musculature of the shoulder, individual muscle segments exist that are capable of exhibiting specific myoelectric intensity and temporal activation patterns. The aim of this thesis was to assess the influence of inter-segment variations in contractile properties on the strategies employed by the CNS when producing voluntary movements. Experiments were designed to test the hypothesis that muscle segment neuromotor coordination (as determined by electromyographic analysis) would be sensitive to the contractile properties of individual muscle segments. A key component was the variation in isometric contraction speed ranging from slow to ballistic.

Mechanomyography (MMG), which is the measure of a muscle's physical dimensional change during contraction, is founded on the premise that the temporal aspect of muscle displacement is reflective of motor unit contractile properties and consequently the muscle fibre type composition. A series of studies were completed to establish the validity of the new Laser-MMG technique for quantifying contractile properties. The results confirmed: 1) the sensitivity of the Laser-MMG technique to modulators of physiological performance (thermal state, fatigue state, and fibre type composition variation between segments); and 2) that the contractile properties of muscle fibres varied between the individual segments of the muscles following maximal percutaneous neuromuscular stimulation (PNS). Most notably, 'slow-twitch' contractile properties were found in muscle segments that have a greater role in producing movement in the coronal plane, while 'fast-twitch' contractile properties were associated with segments having more efficient moment arms to produce movement in the sagittal plane. Furthermore, each of the muscles investigated was associated with a distinctive anatomical distribution of muscle fibre types. Muscle segment contractile properties were heterogeneous and their arrangement appears to reflect the most common or important joint movements. Moreover, the muscle segments located at the

periphery of all three shoulder muscles exhibited faster contractile properties than those located in the middle of the muscle. It appears that this internal arrangement may be a consistent organisational characteristic of radiate muscles.

Muscle segments within the pectoralis major, deltoid and latissimus dorsi muscles were found to be independently controlled by the CNS through manipulation of the myoelectric activation patterns, in particular: onset time; and discharge rate. The lower segments of the pectoralis major and the latissimus dorsi were identified as prime mover segments, initiating the movement and contributing the greatest myoelectric intensity. The immediately superior segments were classified as assistant movers, activating after the prime movers and contributing less to the overall movement. Furthermore, similarities in neuromotor coordination were identified between adjacent segments of individual muscles. The sequential "wave of segment activation" identified within each whole muscle appeared to ignore the anatomical boundaries between muscles, suggesting that the CNS coordinates individual muscle segments rather than the whole muscle as one unit in order to complete a motor task. This further complicates the process of controlling motor tasks as there appear to be no defined limits of muscles to which discrete functions can be applied.

Coordination between prime mover segments of agonist muscles was identified, with the lower segments of pectoralis major and latissimus dorsi showing no significant difference in any of the temporal myoelectric measures. The similarity in neuromotor coordination between these segments may be the result of a common drive, suggesting that the CNS uses a simple strategy of combining the segments into one functional unit.

No gross disordering of the muscle segments' onset was identified within any of the investigated muscles, with regard to movement speed. However, the pectoralis major exhibited altered relative timing between the segments. This was particularly evident during the fast movement. The sequential "wave of activation" present during the slow movements became disordered as muscle contraction speed was increased. During fast contraction, the assistant mover segments within pectoralis major were activated later than the prime mover segments changing the relative timing of their activation. This indicates that the CNS may initially prioritise the activation of only the most essential muscle segments to commence the movement during ballistic movements, perhaps due to the imposed time constraints. This form of change in relative timing can be interpreted as a direct reflection of the differences in muscle segment fibre type composition and hence the neuromotor control of the muscle segments involved in producing the movement. Most notably, variation to the control of muscle segment excitation and contraction onset exist in the more centrally located muscle segments that exhibit slower segment contractile properties. This finding appears logical when coupled with the finding of homogeneous myoelectric peak activity. The CNS must manipulate the onset of these slower contracting segments, especially during fast movements, in order to allow enough time for all segments to achieve a uniform peak of muscle activity that occurs just prior to peak force.

The variations and coordination of contractile properties, myoelectric properties and electromyographic burst patterns between adjacent muscle segments within the same skeletal muscle confirms the notion that for CNS control, individual muscle segments are considered as sub-volumes of muscle tissue that require individual neuromotor control – that they are, in effect, muscles within muscles.