

Rethinking motor unit activation in health and disease



Jason J. Kutch, Ph.D.
Research Assistant Professor
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Why rethink motor unit activation?

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1. Expanding interest in **altered** motor unit activation

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c) **Aging** (Enoka et al. 1999, Akataki et al. 2003)

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- d) **Chronic pain** (Hetrick et al. 2006, Tucker et al. 2009)



Why rethink motor unit activation?

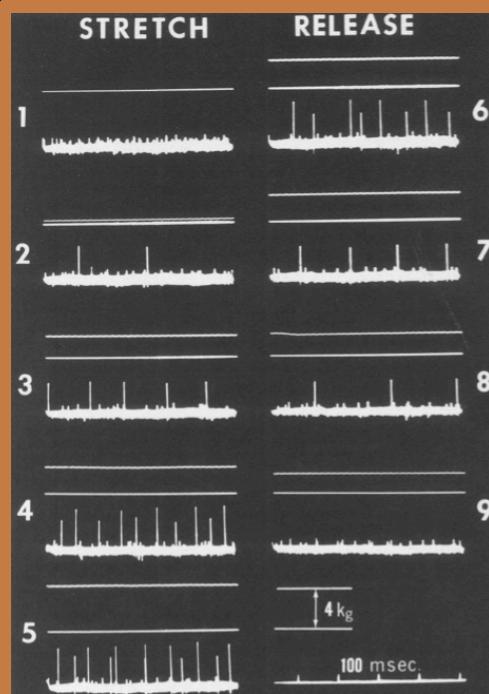
1. Expanding interest in **altered** motor unit activation

- a) **Stroke** (Gemperline et al. 1995, Lewek et al. 2007, Mottram et al. 2009)
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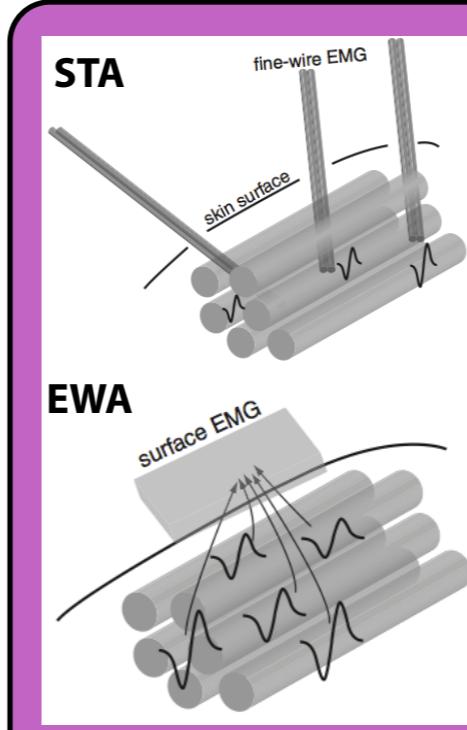
2. New approaches for rapid non-invasive characterization of motor unit activity

Overview



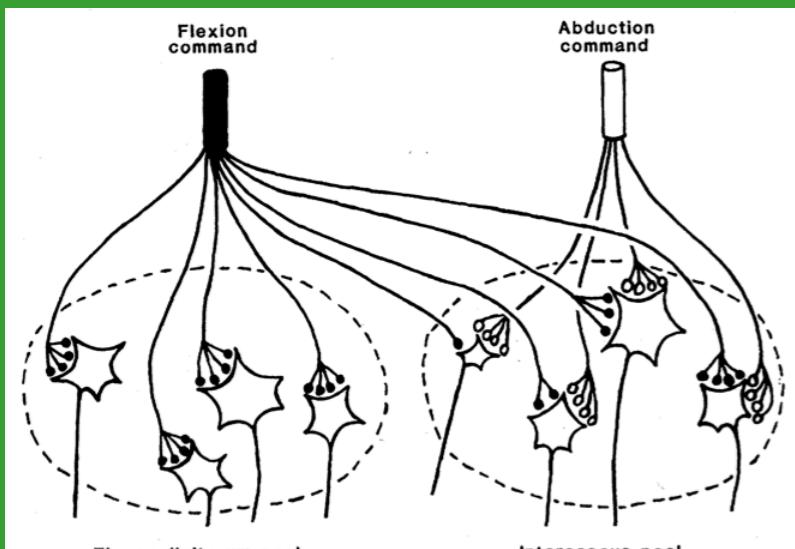
Henneman et al., 1965

Background



Kutch et al., 2010

New Approach



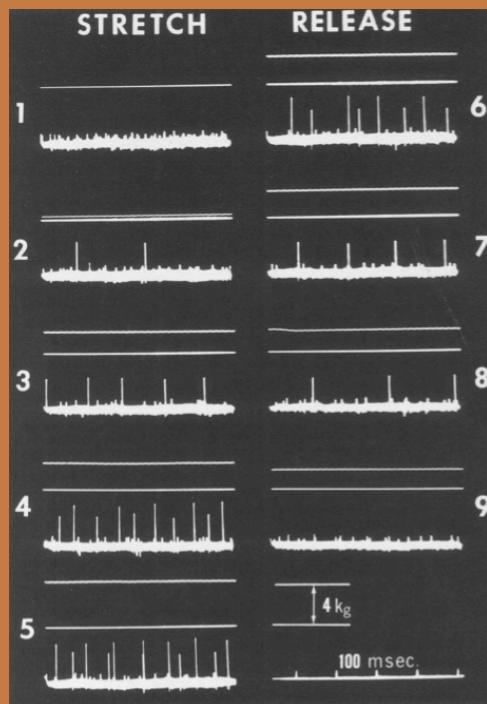
Desmedt & Godaux, 1981

Prelim. Data: Direction



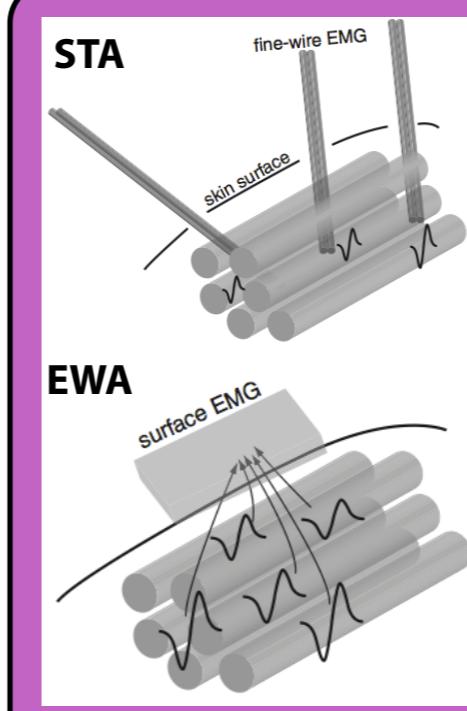
from C. Mottram, w/ Permission

Prelim. Data: Stroke



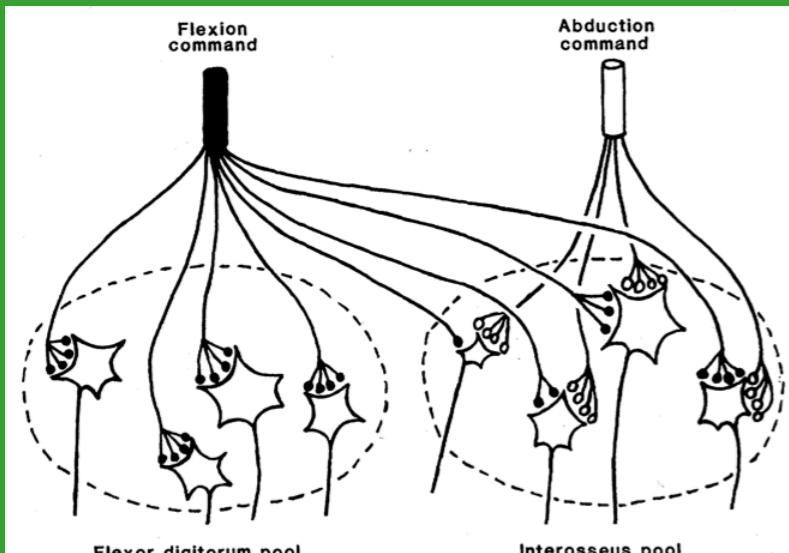
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New Approach



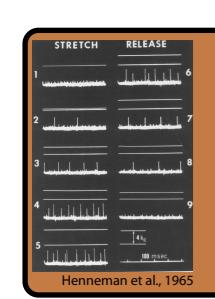
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Prelim. Data: Direction

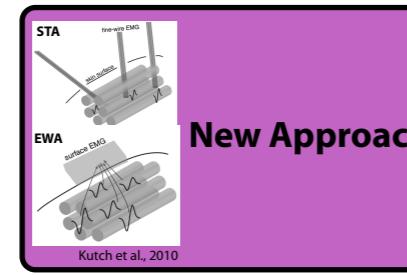


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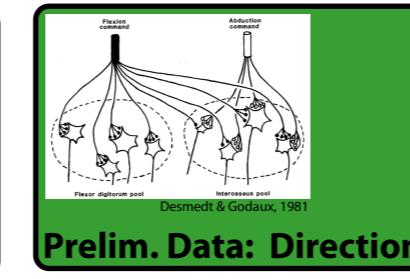
Prelim. Data: Stroke



Background



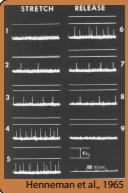
New Approach



Prelim. Data: Direction



Prelim. Data: Stroke



Background



New Approach

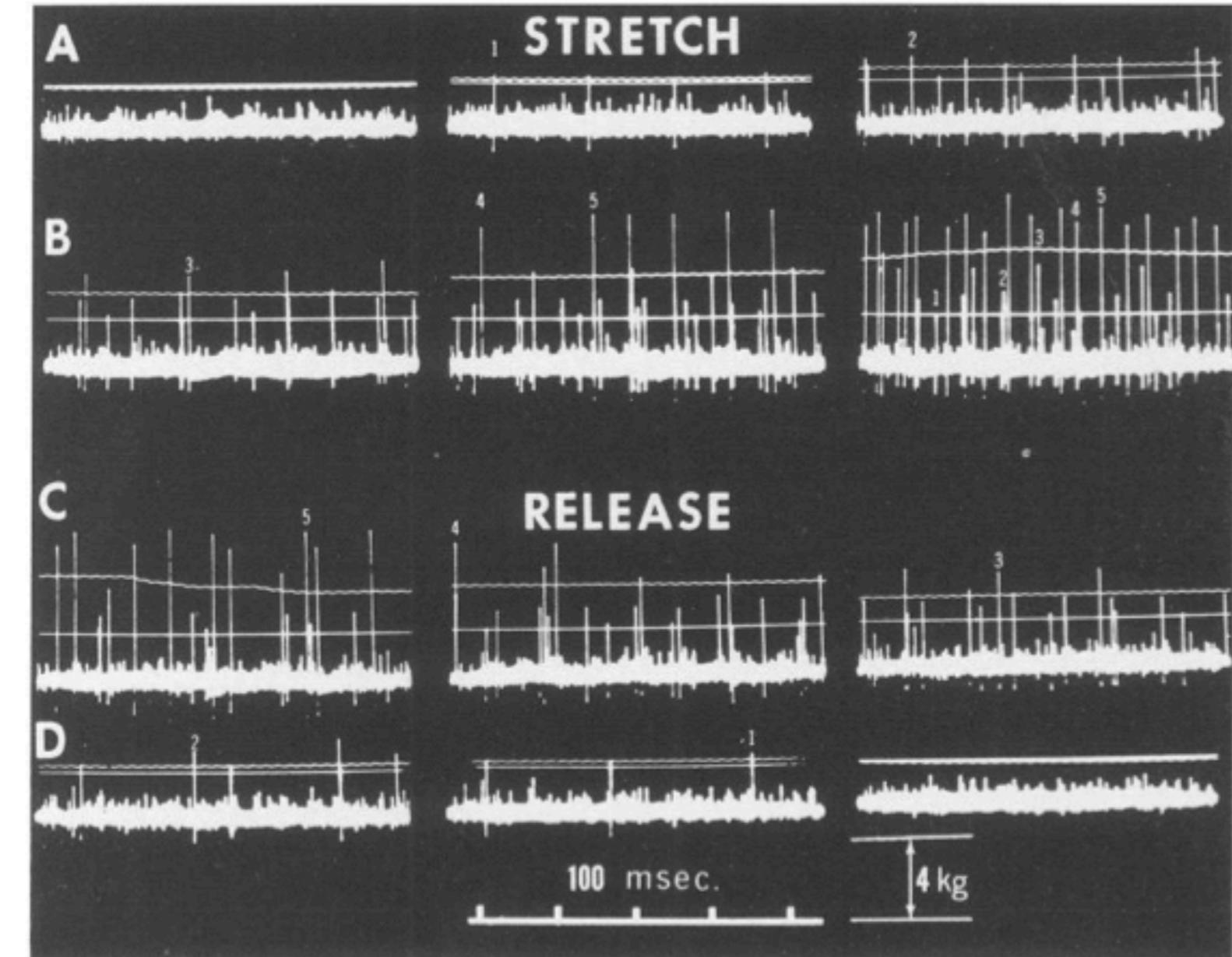
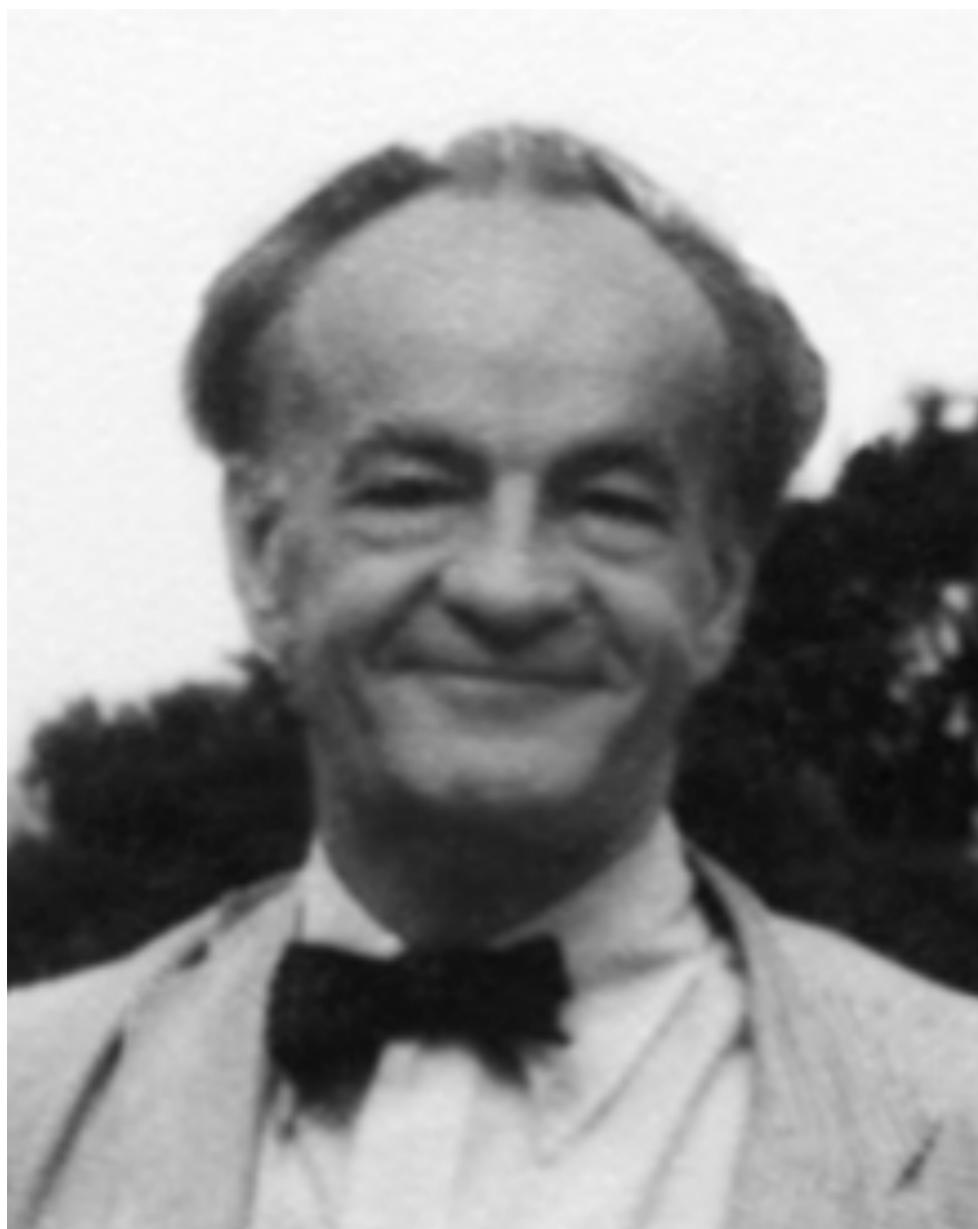


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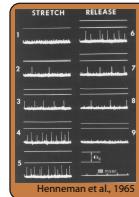


Prelim. Data: Stroke

Elwood Henneman (1915-1996)



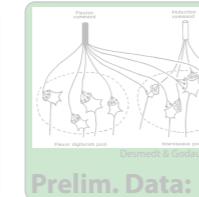
Henneman et al., 1965



Background



New Approach

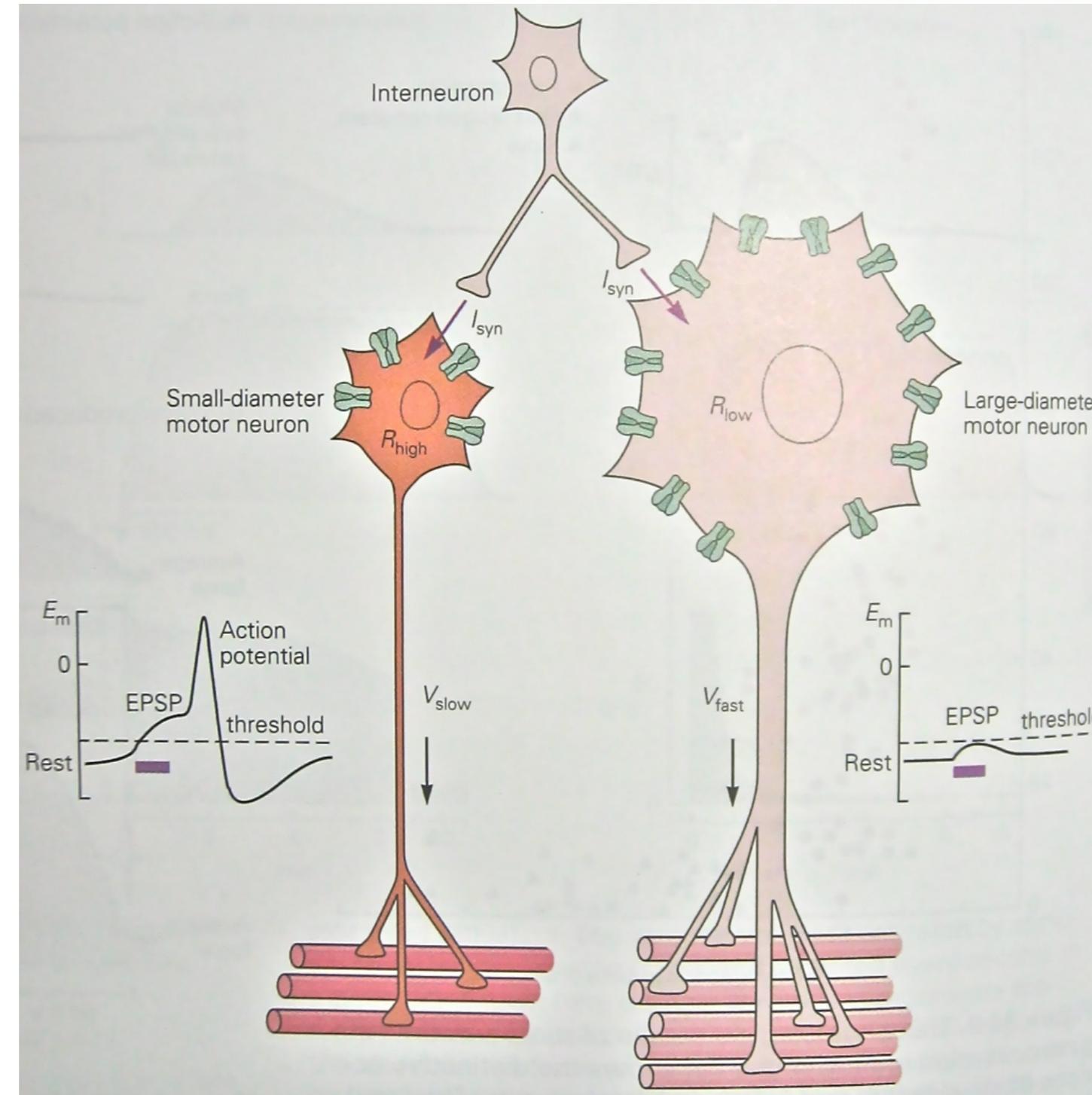


Prelim. Data: Direction

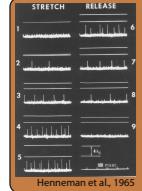


Prelim. Data: Stroke

Recruitment: Input resistance



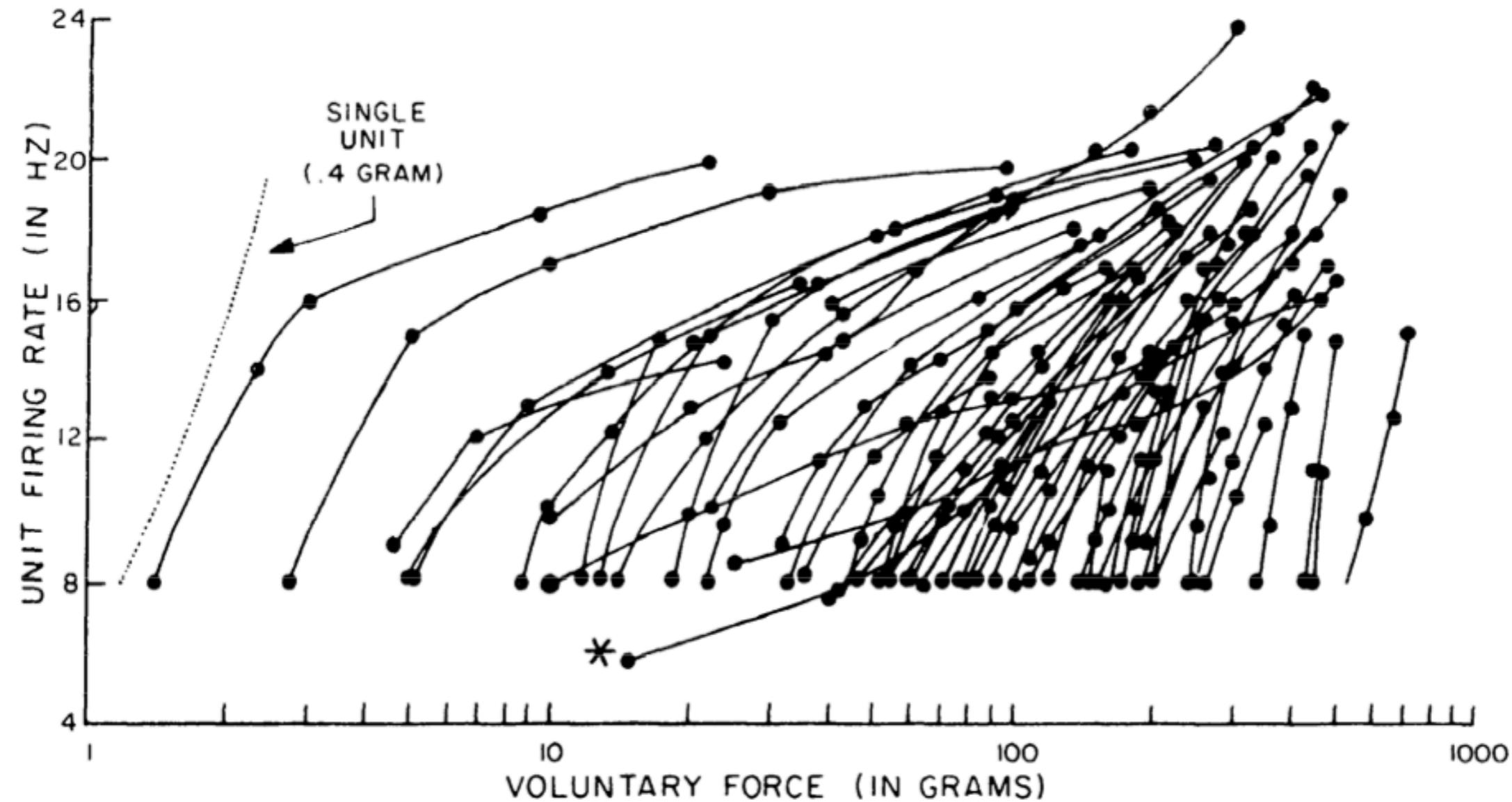
from Kandel, Schwartz, and Jessell, 4th ed.



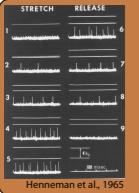
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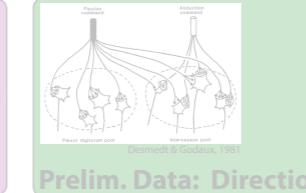
Recruitment and rate modulation



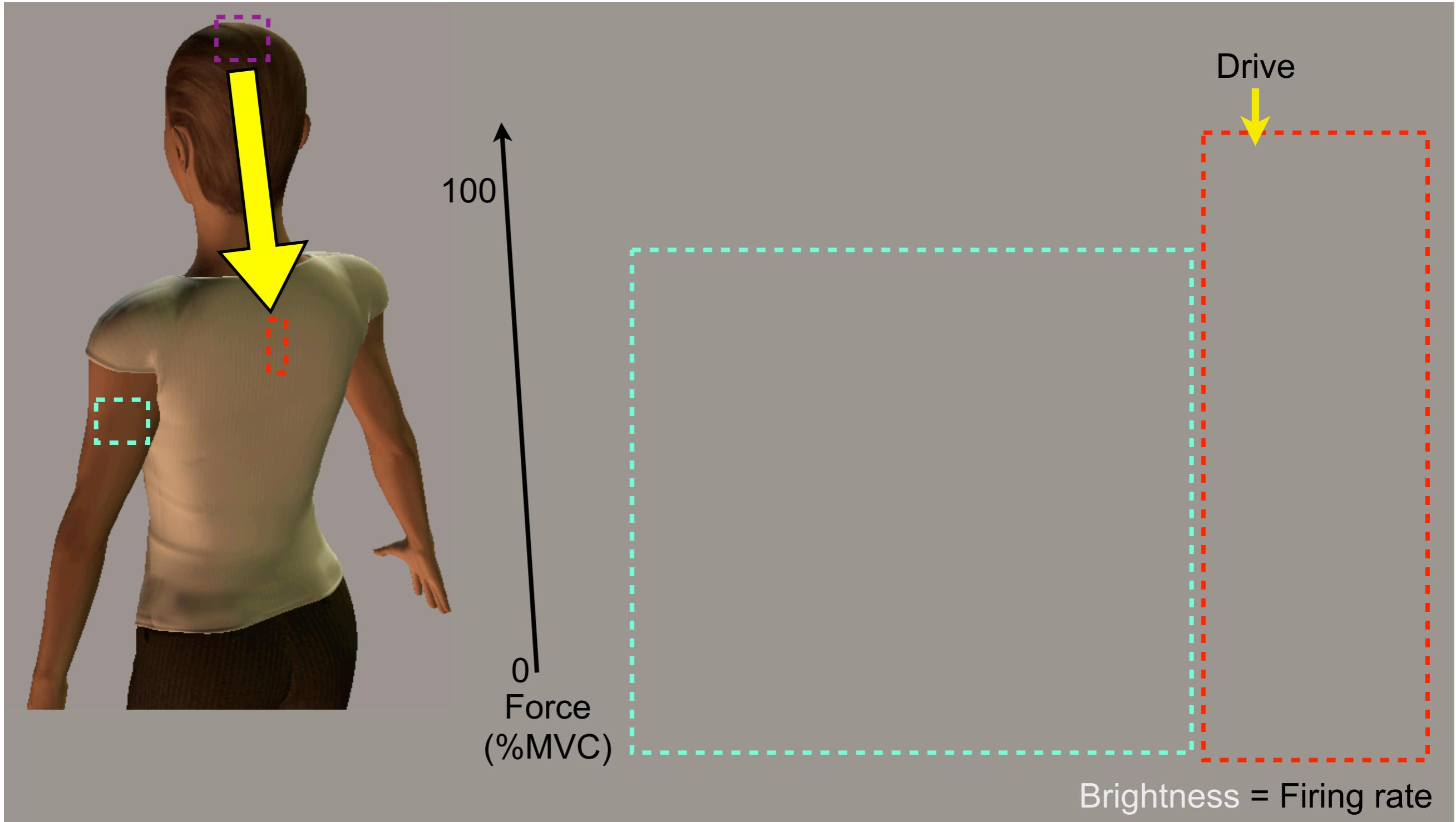
Monster and Chan, 1977

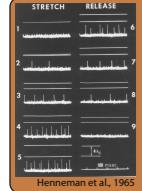


Background



Myth (n.): a widely held but false belief or idea

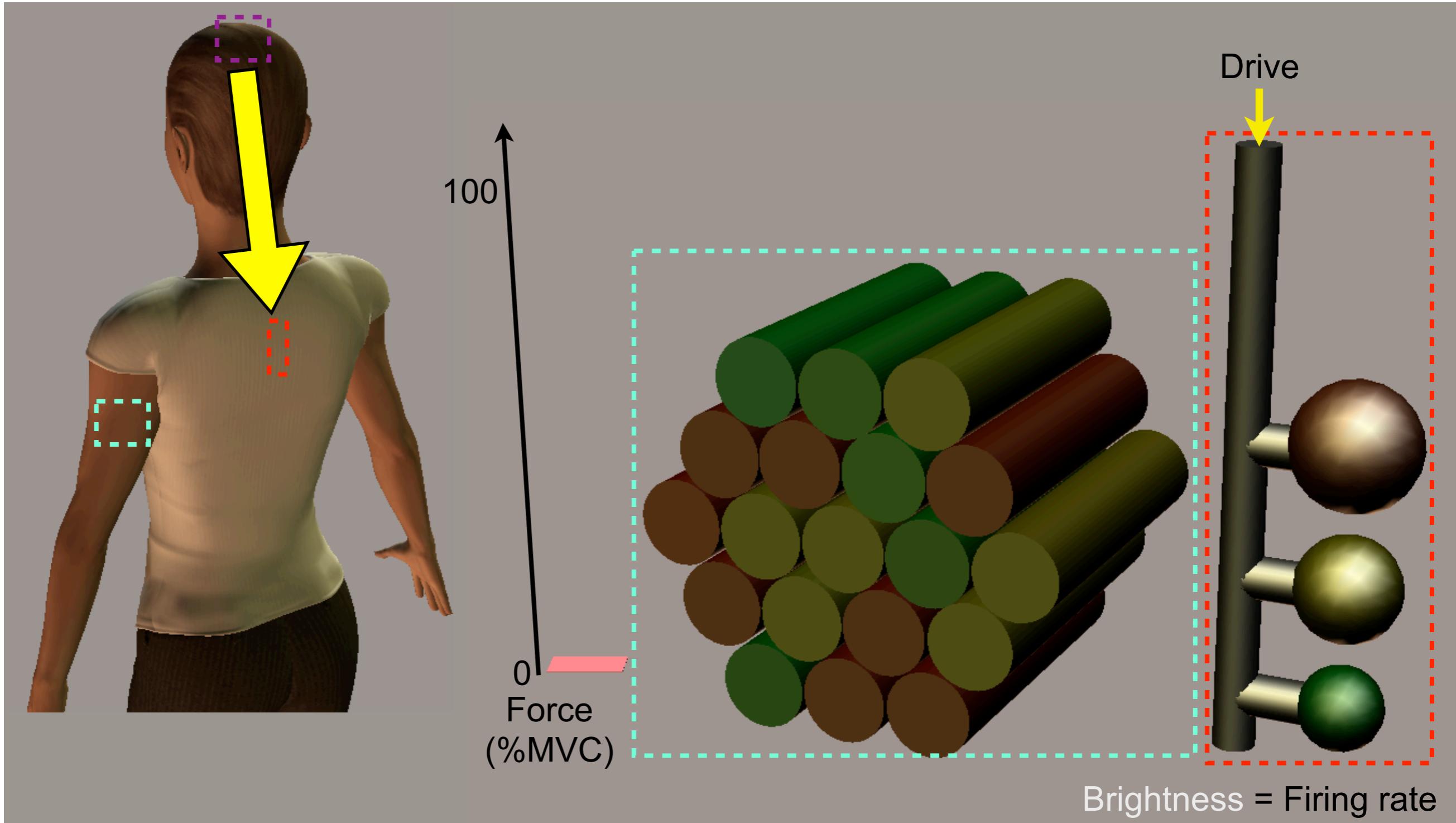




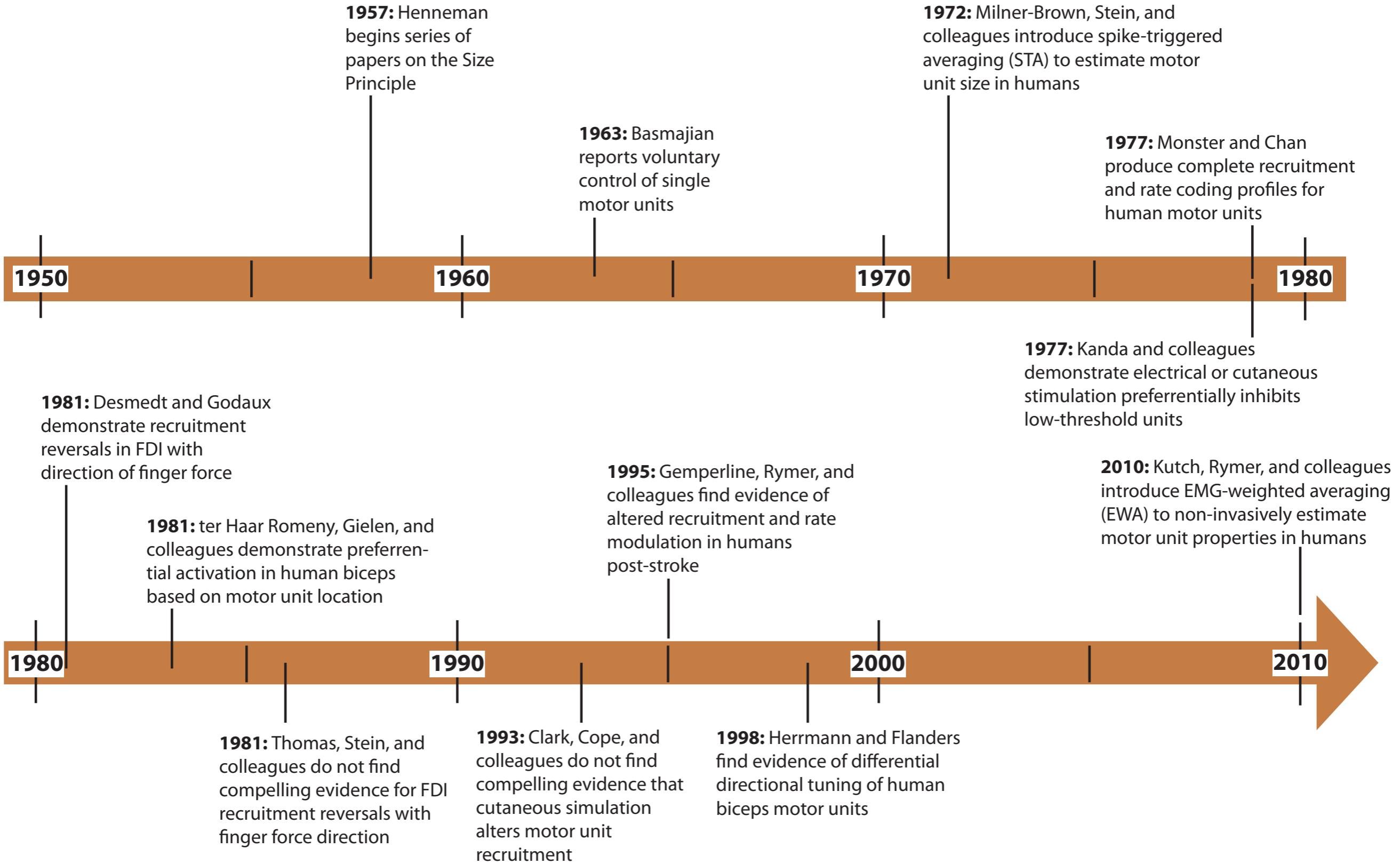
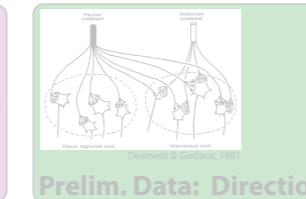
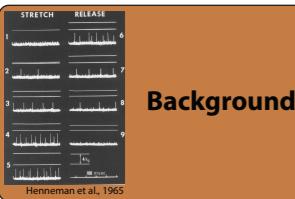
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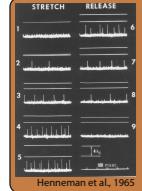


Myth (n.): a widely held but false belief or idea



Timeline





Background



New Approach



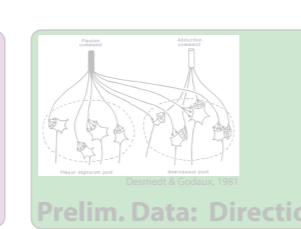
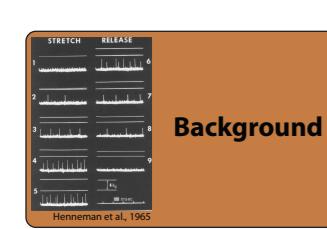
Prelim. Data: Direction



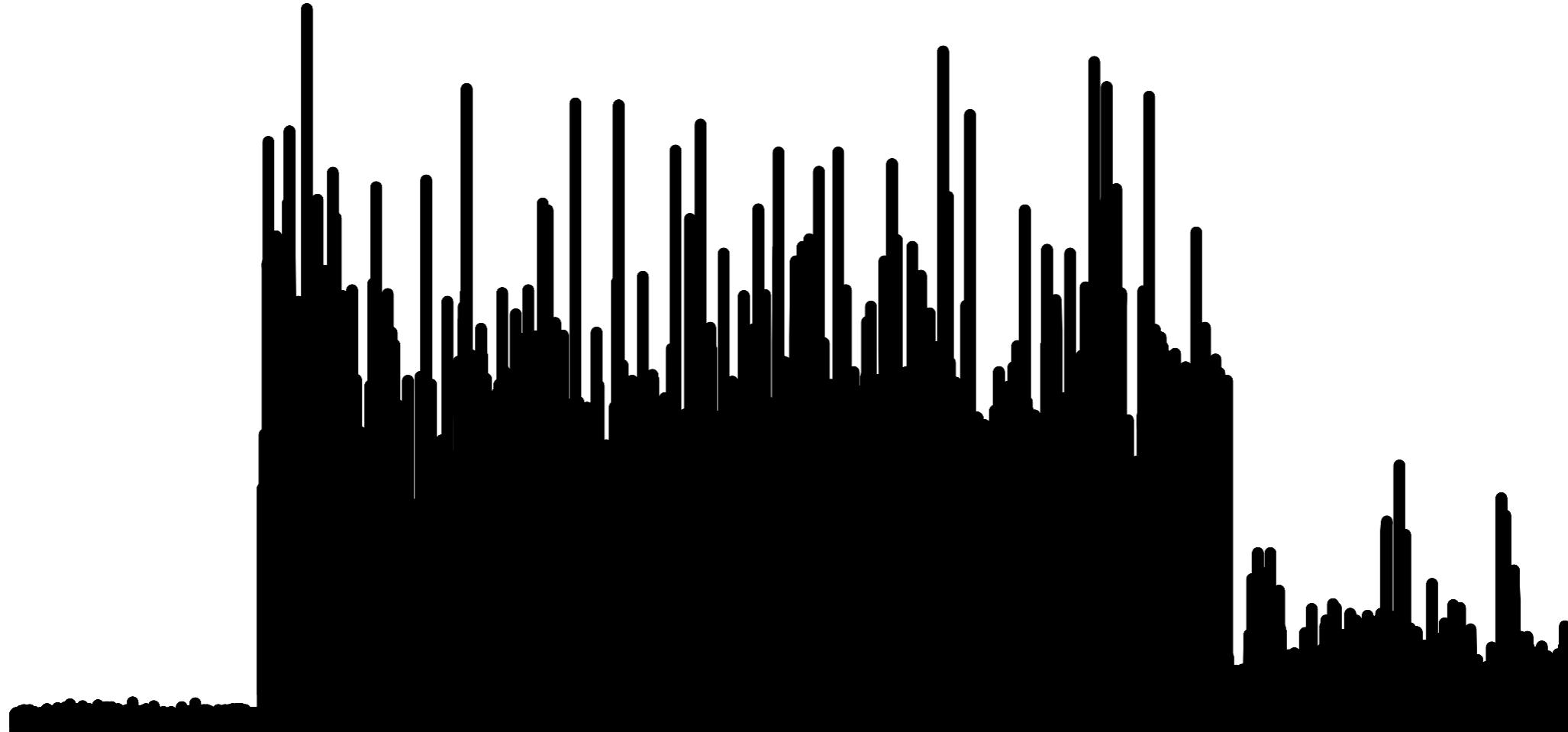
Prelim. Data: Stroke

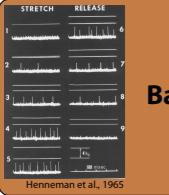
Single MU recording





Many MU: surface EMG

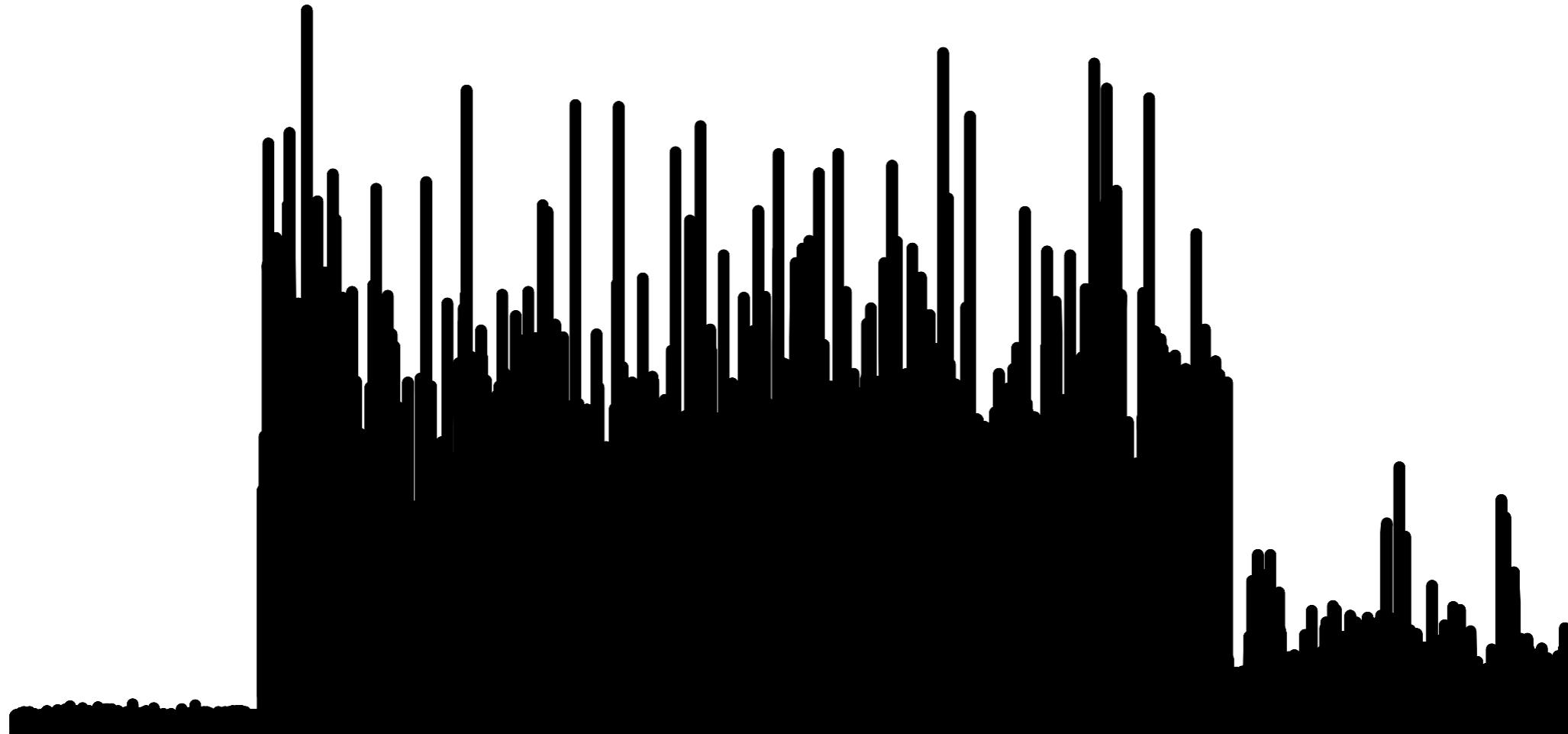




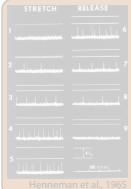
Background



Many MU: surface EMG



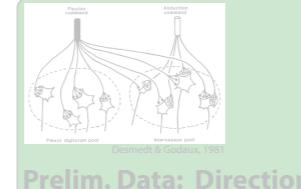
Interference pattern: Just overall force, or also recruitment and rate modulation?



Background



New Approach



Prelim. Data: Direction



Prelim. Data: Stroke

EMG-weighted averaging (EWA): a new approach

J Neurophysiol 103: 3535–3546, 2010.
First published April 14, 2010; doi:10.1152/jn.00956.2009.

Innovative Methodology

Extraction of Individual Muscle Mechanical Action From Endpoint Force

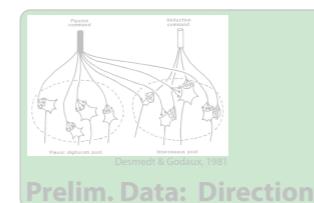
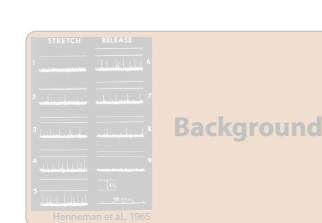
Jason J. Kutch,^{1,2} Arthur D. Kuo,³ and William Z. Rymer²

¹Applied and Interdisciplinary Mathematics and ³Mechanical Engineering and Biomedical Engineering, University of Michigan, Ann Arbor, Michigan; and ²Sensory Motor Performance Program, Rehabilitation Institute of Chicago, Chicago, Illinois

Submitted 29 October 2009; accepted in final form 12 April 2010

Kutch JJ, Kuo AD, Rymer WZ. Extraction of individual muscle mechanical action from endpoint force. *J Neurophysiol* 103: 3535–3546, 2010. First published April 14, 2010; doi:10.1152/jn.00956.2009. Most motor tasks require the simultaneous coordination of multiple muscles. That coordination is poorly understood in part because there is no noninvasive means of isolating a single muscle's contribution to the resultant endpoint force. The contribution of a single motor unit to isometric tasks can, however, be characterized using the spike-triggered averaging (STA) technique, applied to a single motor unit's spike train. We propose that a technique analogous to STA, which we call electromyogram (EMG)-weighted averaging (EWA), can be applied to surface EMGs to extract muscle mechanical action from the

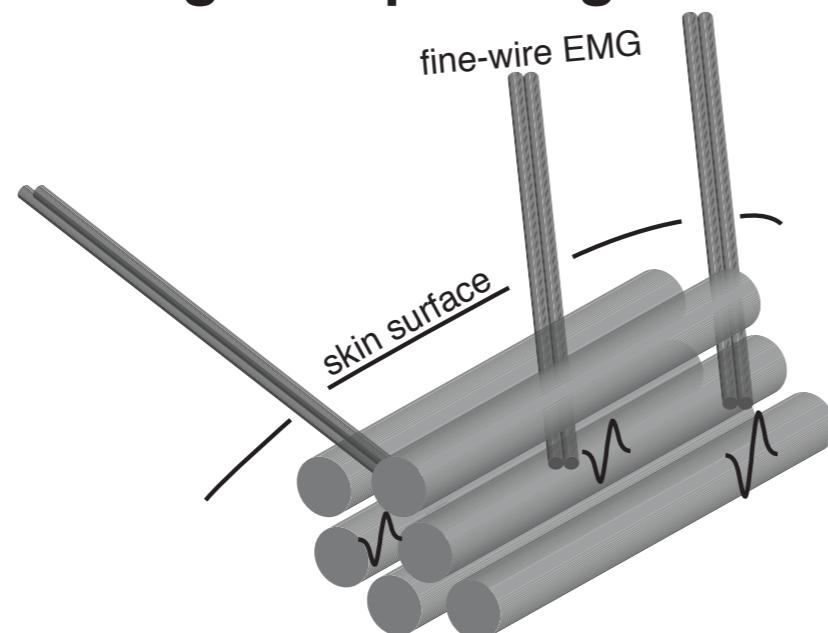
(Fowler et al. 2001), and at the single motor unit level, from surface electrode arrays (Merletti et al. 2003), intramuscular recording (Moritz et al. 2005), and intra-neural micro stimulation (Keen and Fuglevand 2004; Thomas et al. 1990b) during isometric force production tasks. But the bulk properties of a muscle or a motor unit population are difficult to estimate noninvasively. We propose a means of characterizing a muscle's contribution to applied endpoint force using whole-muscle surface electromyogram (EMG), which may obviate the need for invasive EMG measurements.



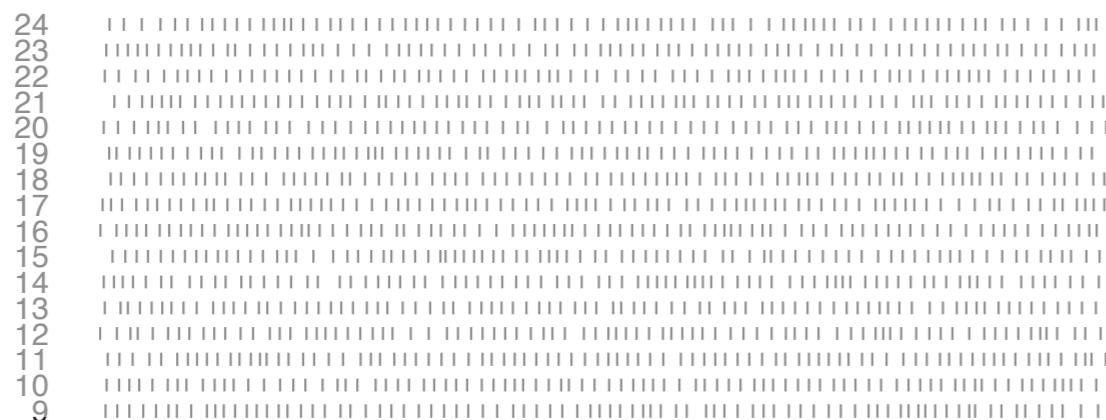
EMG-weighted averaging (EWA): a new approach

Spike-triggered averaging (STA)

A. Recording multiple single MU

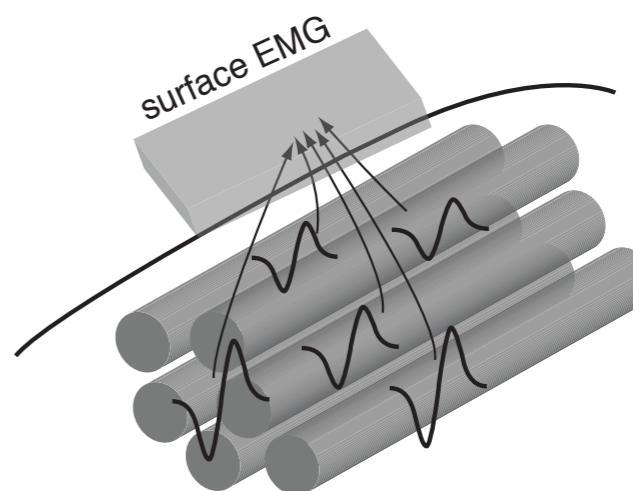


C. Spike trains

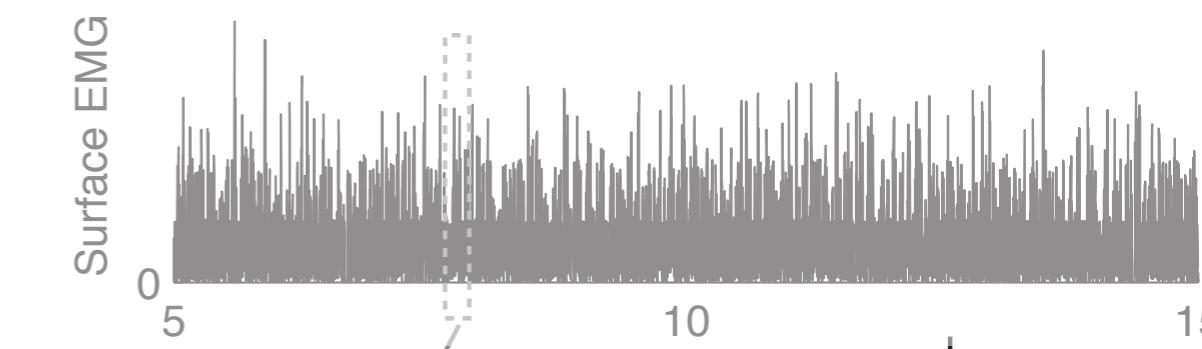


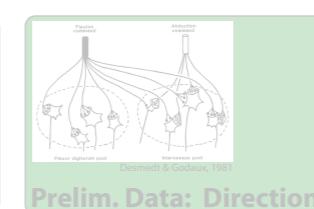
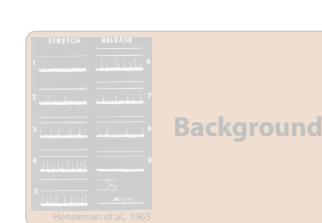
EMG-weighted averaging (EWA)

B. Recording many MU

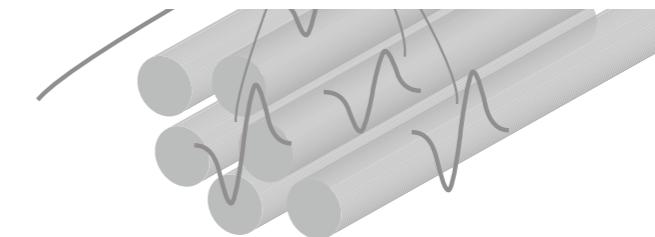
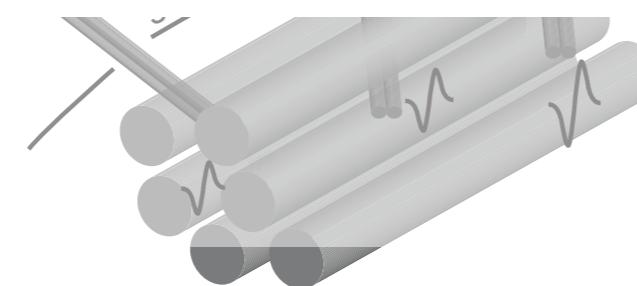


D. Surface EMG

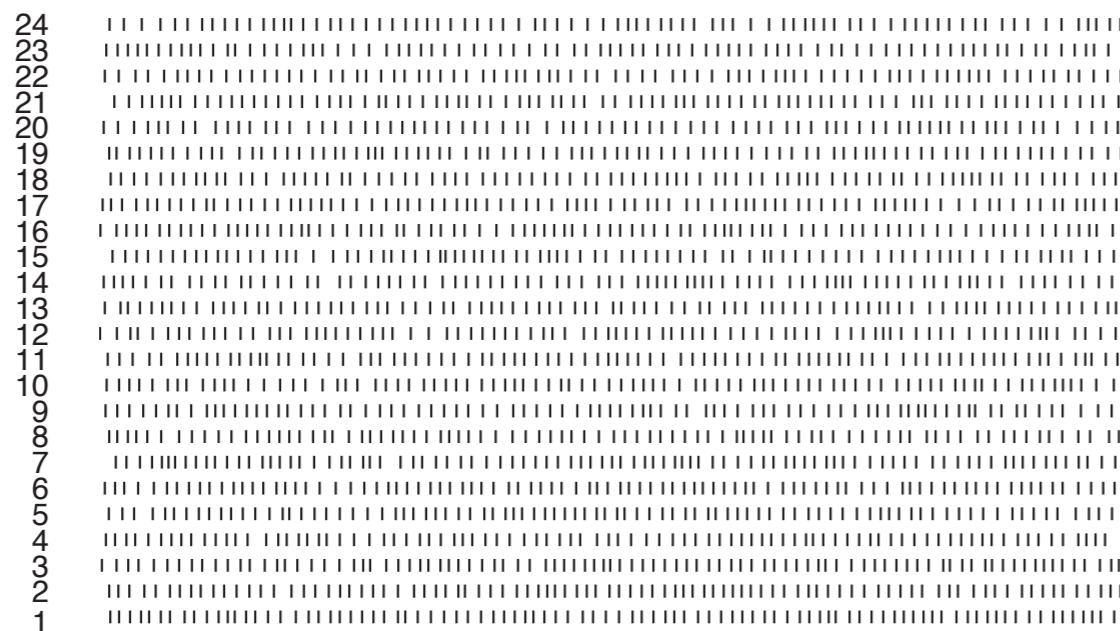




EMG-weighted averaging (EWA): a new approach



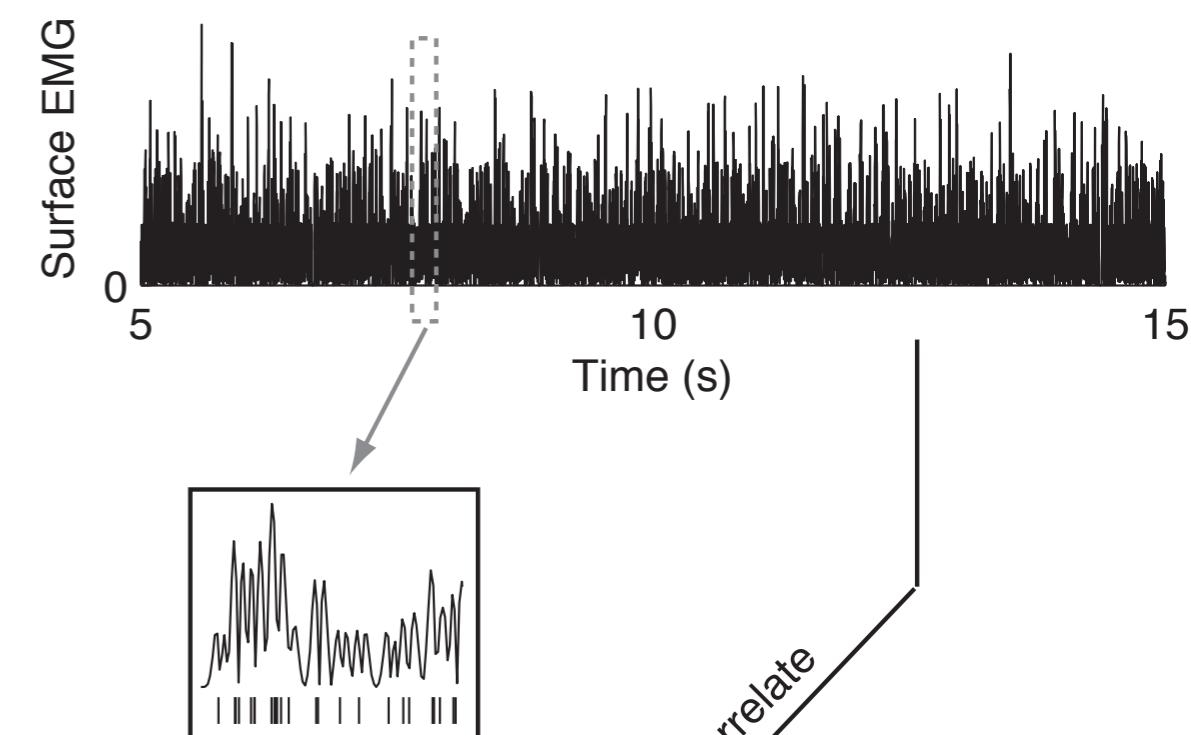
C. Spike trains



Superpose spike trains

cross-correlate

D. Surface EMG



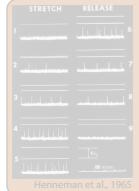
E. Force fluctuations



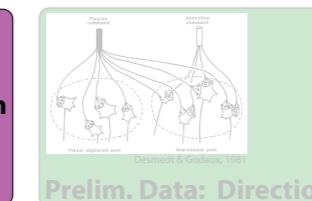
cross-correlate

**F. STA based on superposed spike train
= avg. STA across MU**

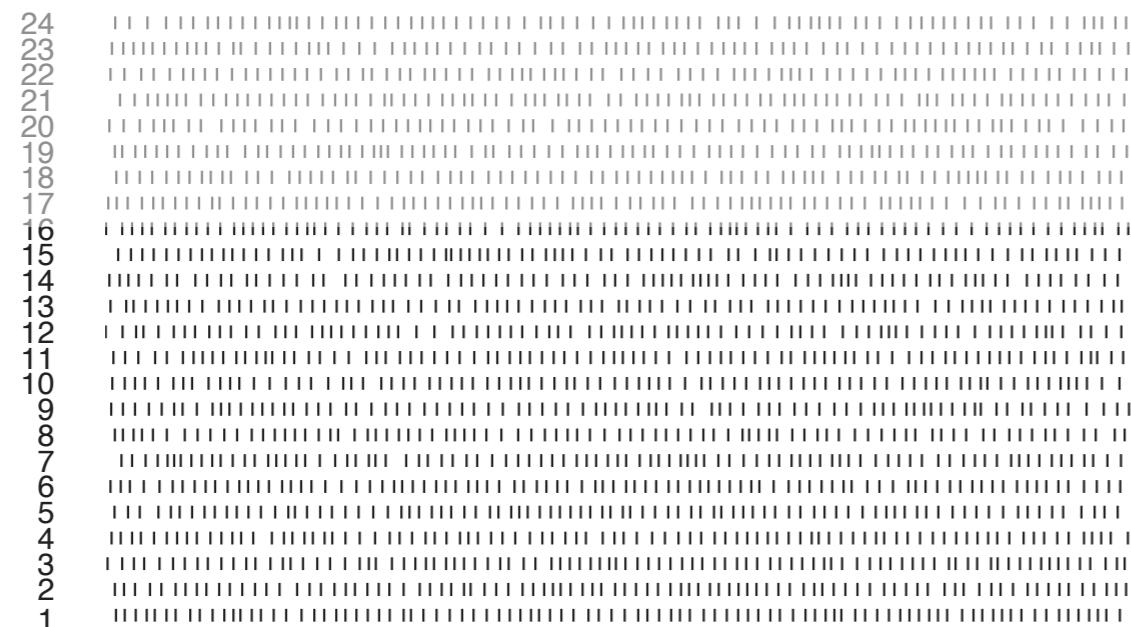
G. EWA ≈ average. STA across MU



Background



EMG-weighted averaging (EWA): a new approach



Superpose spike trains

cross-correlate

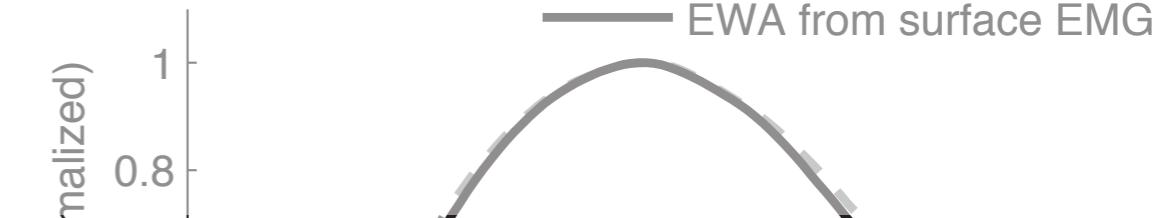
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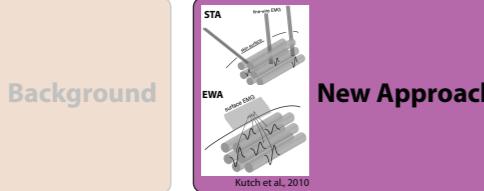
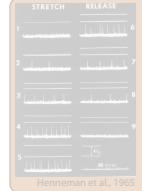
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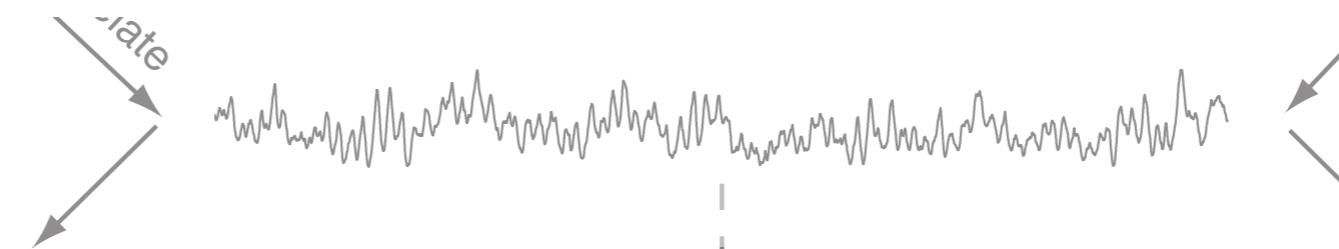
G. EWA \approx average. STA across MU

- STA from individual MU
- Avg. STA across MU
- - - STA - superposed spike train

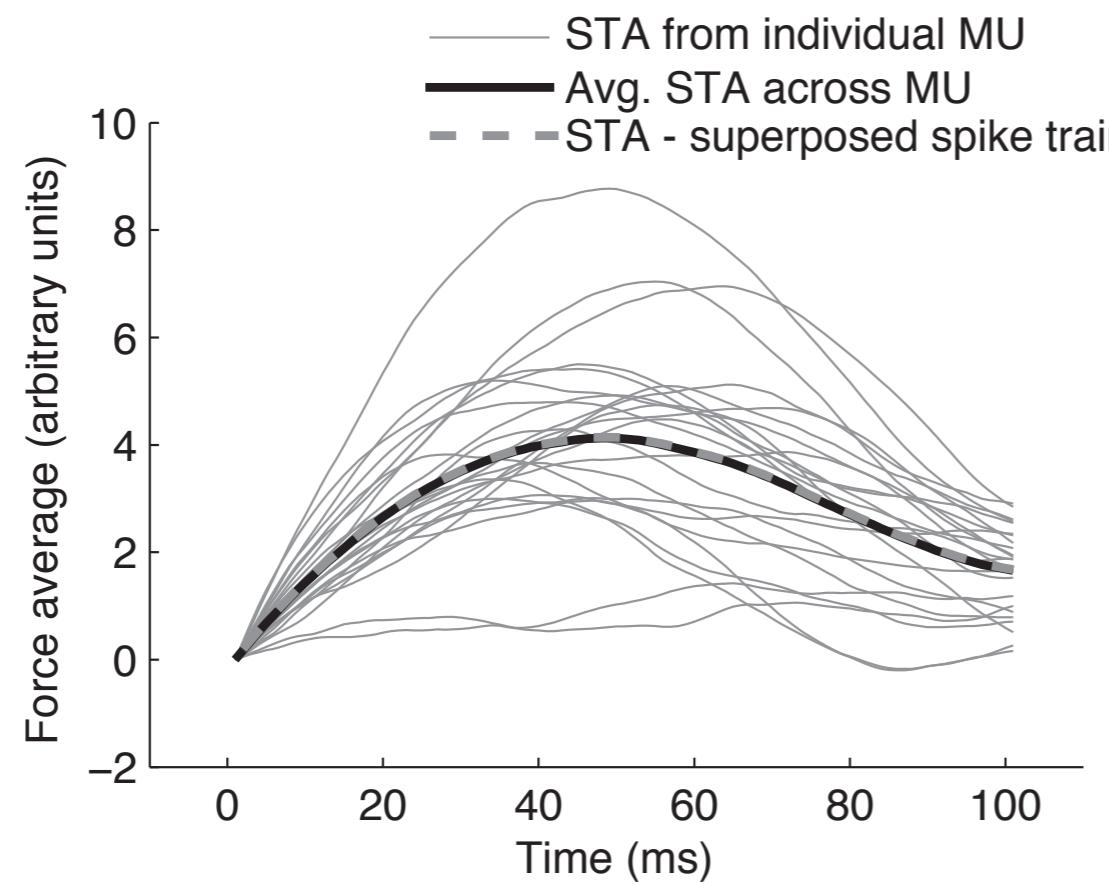




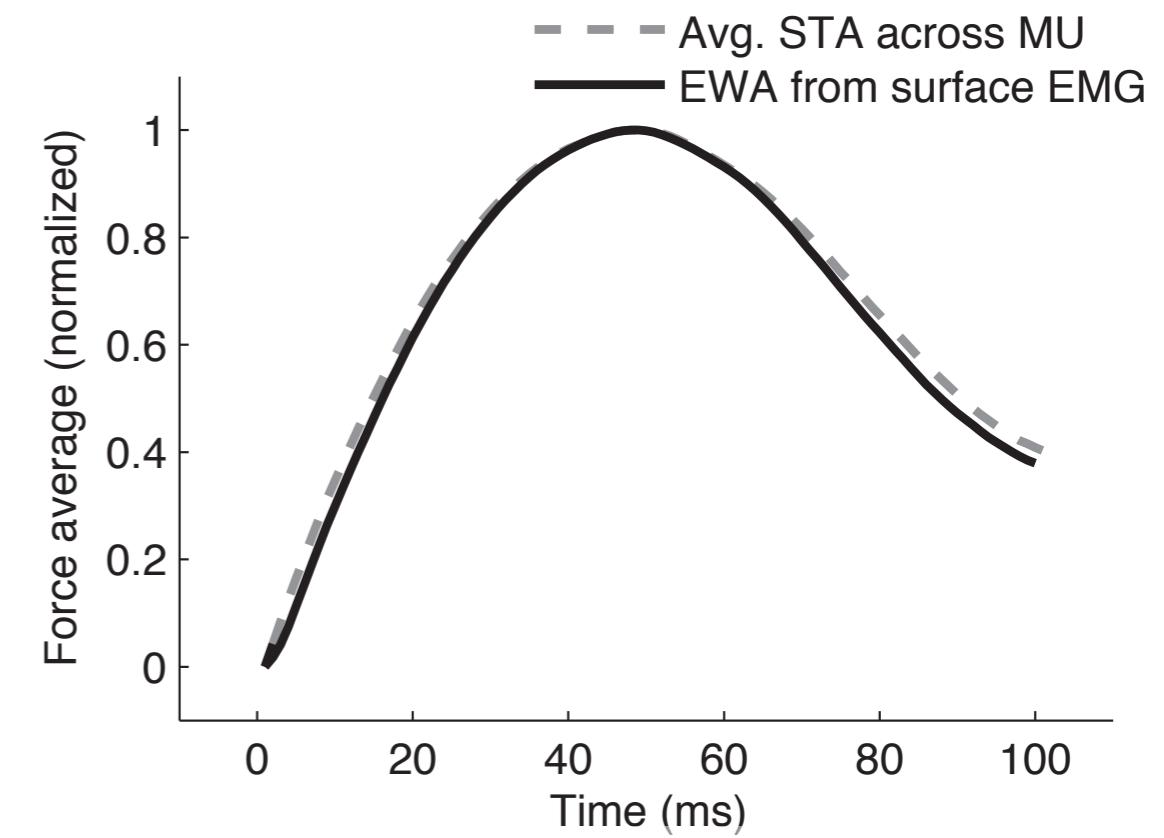
EMG-weighted averaging (EWA): a new approach

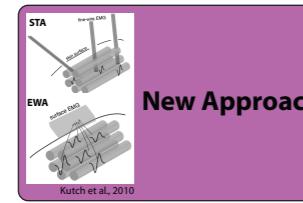


F. STA based on superposed spike train
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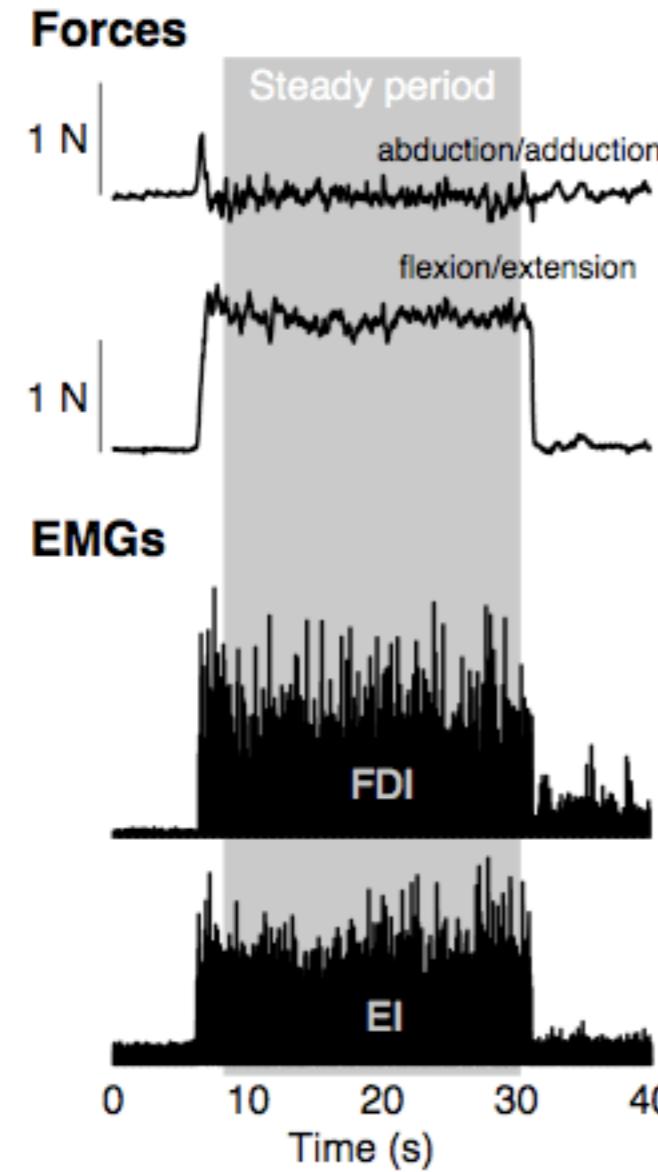


G. EWA \approx average. STA across MU

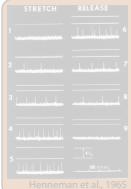




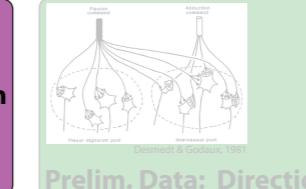
A. Time domain data



EWA looks a lot like STA

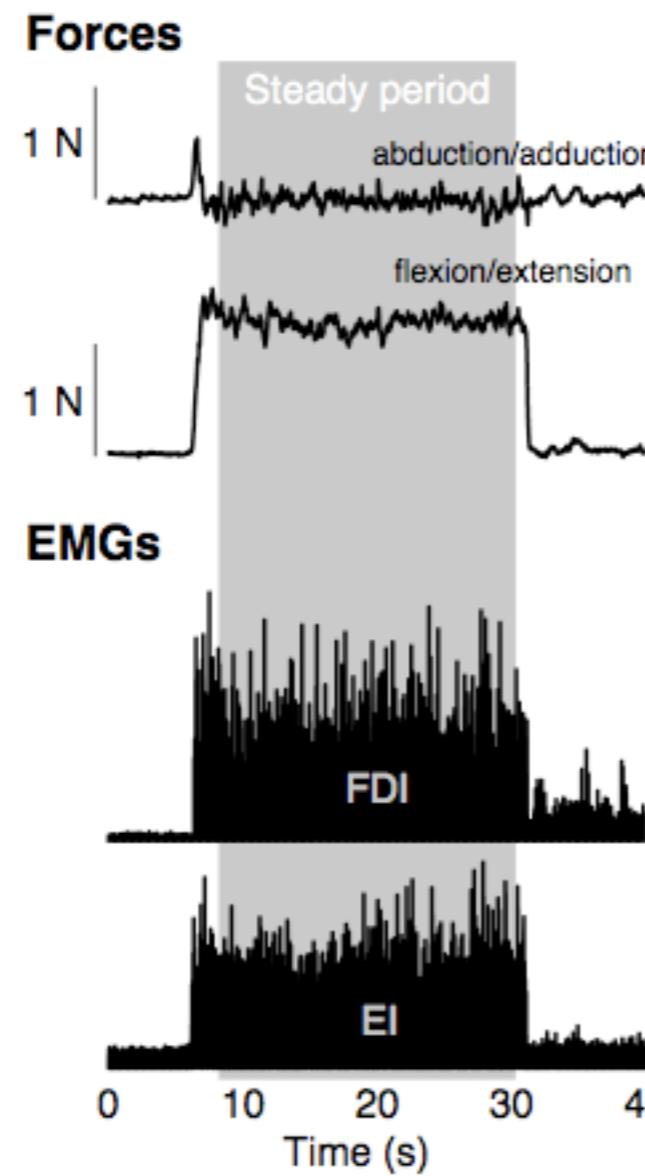


Background



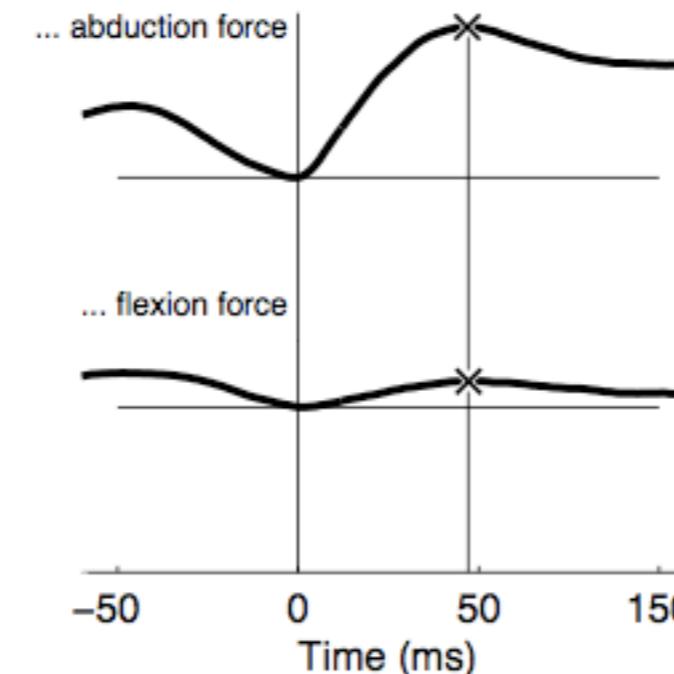
EWA looks a lot like STA

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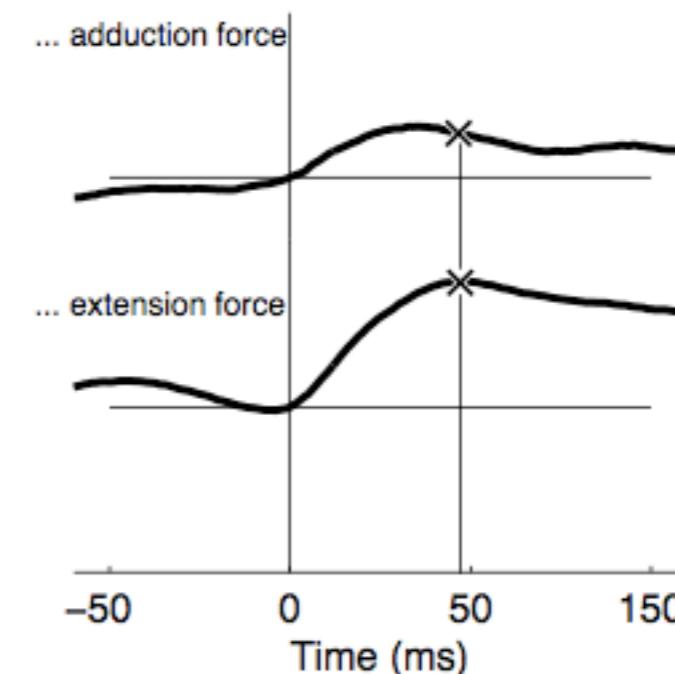


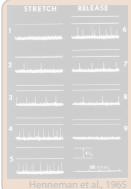
B. EWA waveforms

FDI EMG cross-correlated with ...

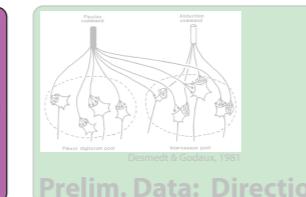


EI EMG cross-correlated with ...



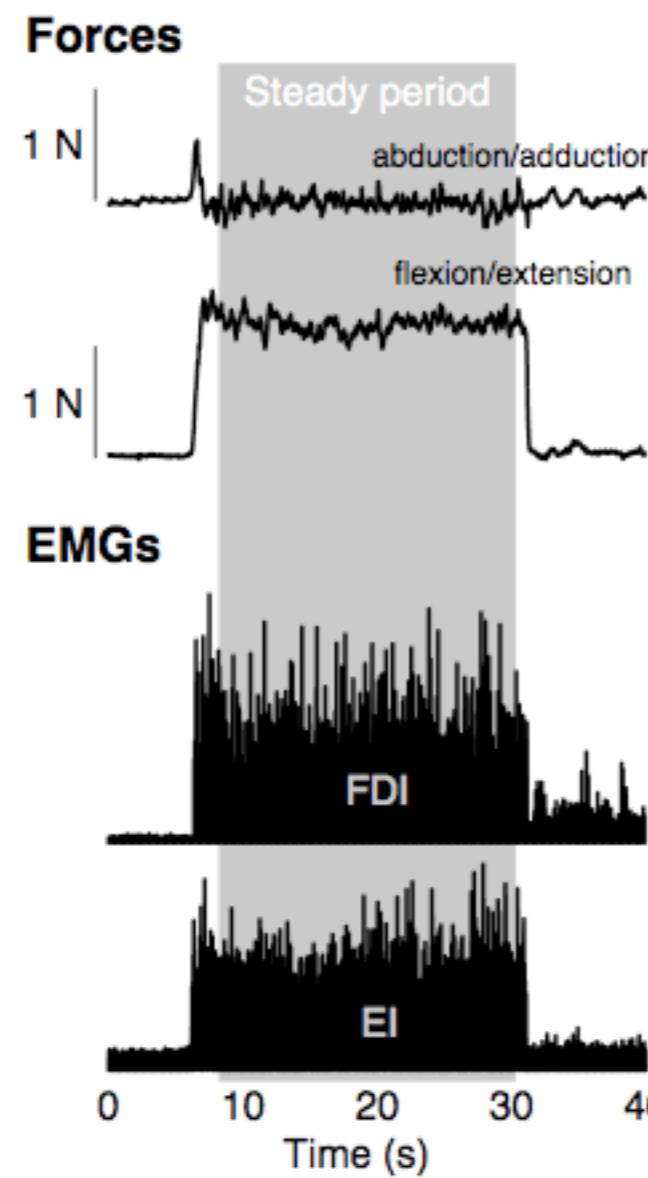


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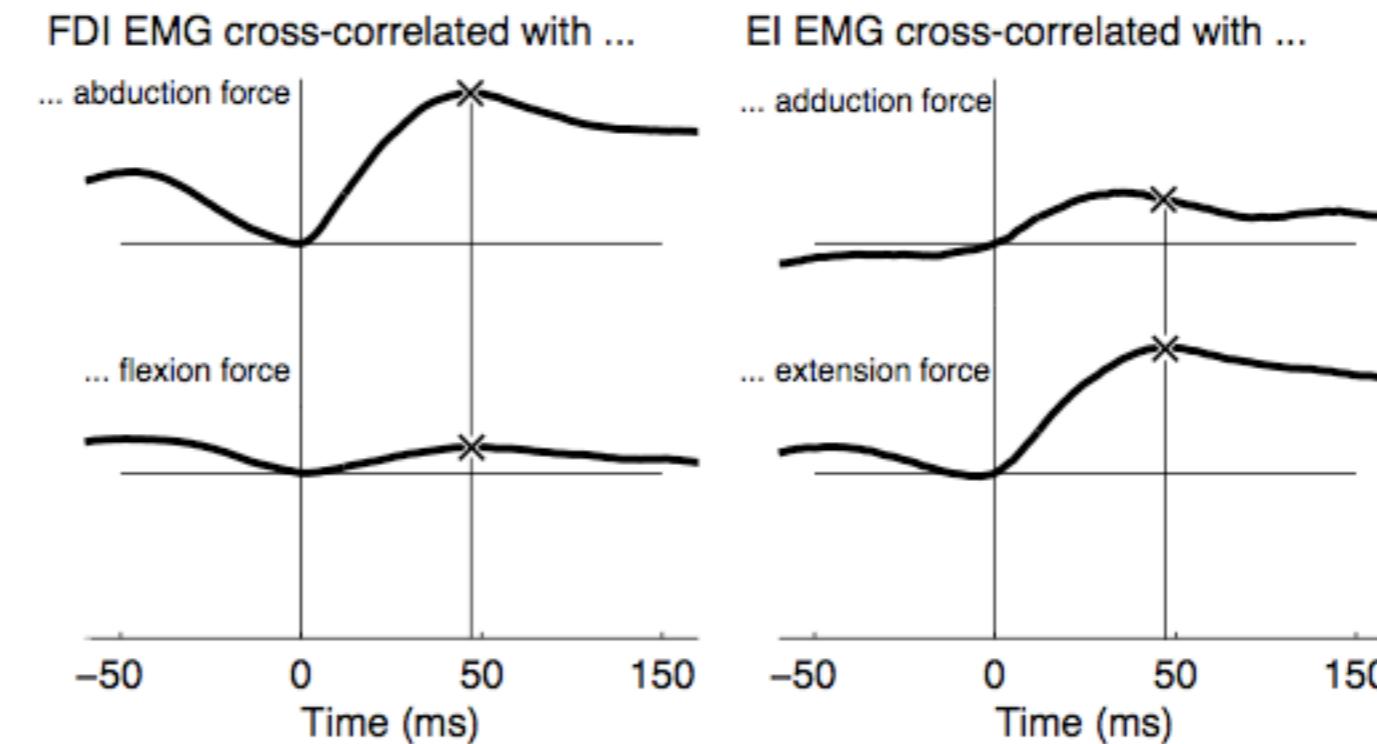


EWA looks a lot like STA

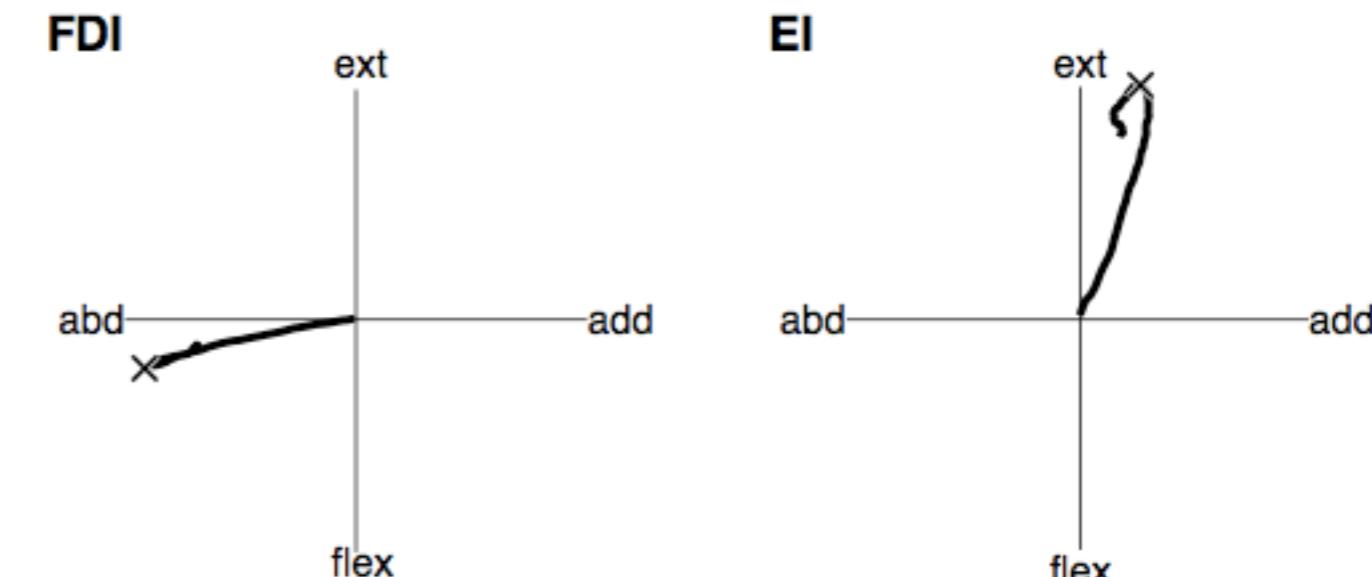
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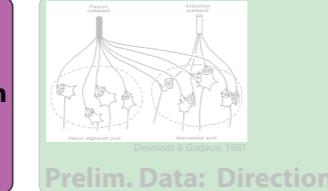
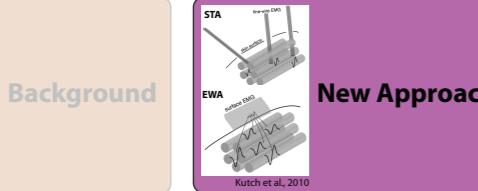
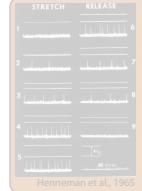


B. EWA waveforms



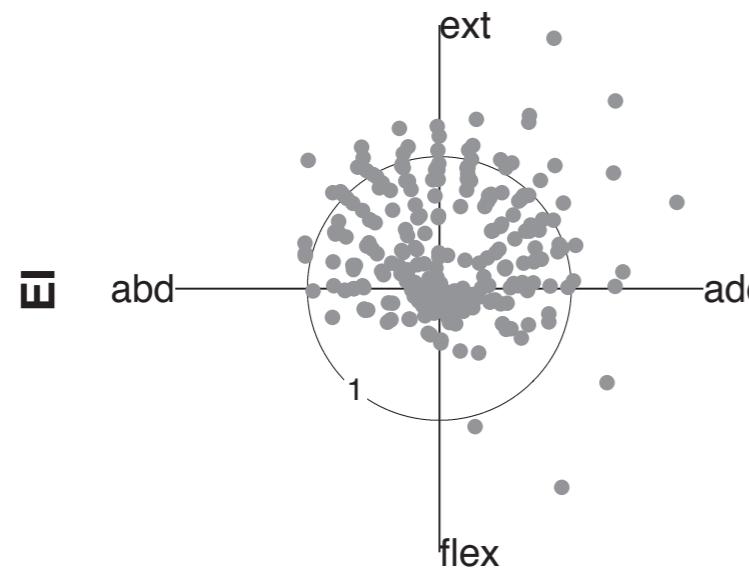
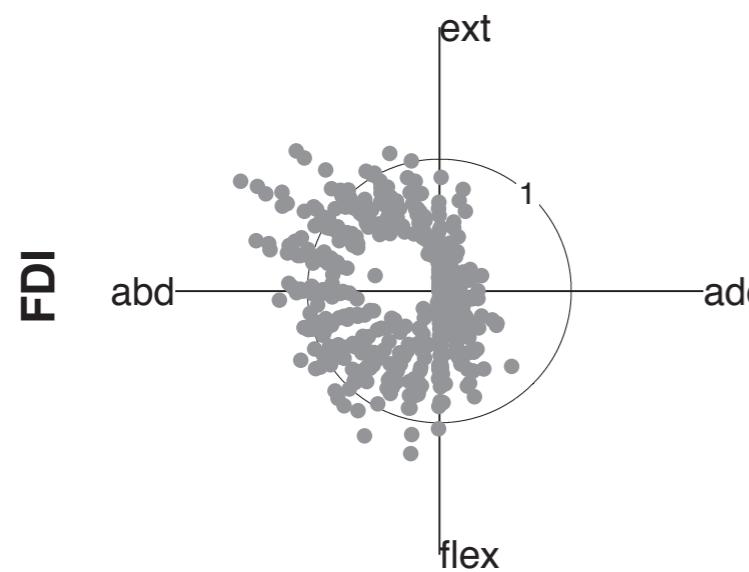
C. EWA trajectories



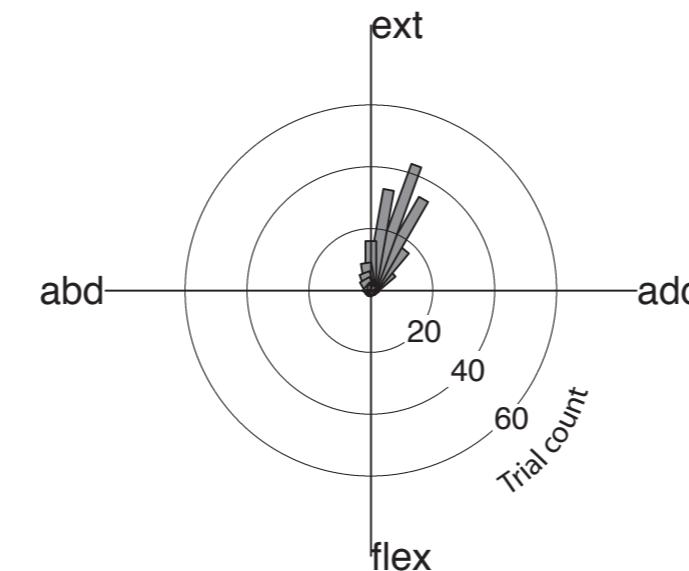
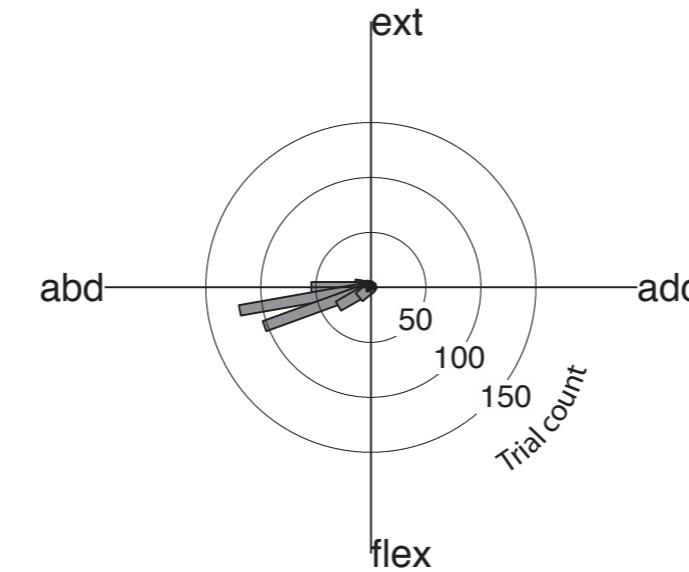


EWA has the right direction and time course

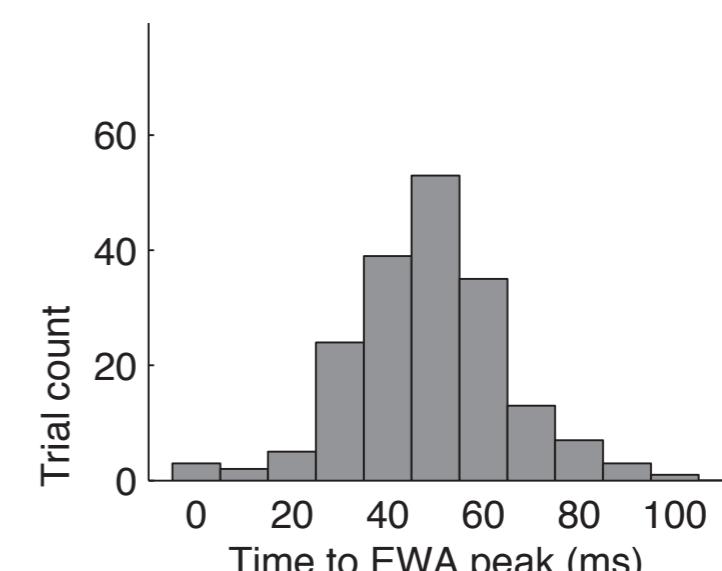
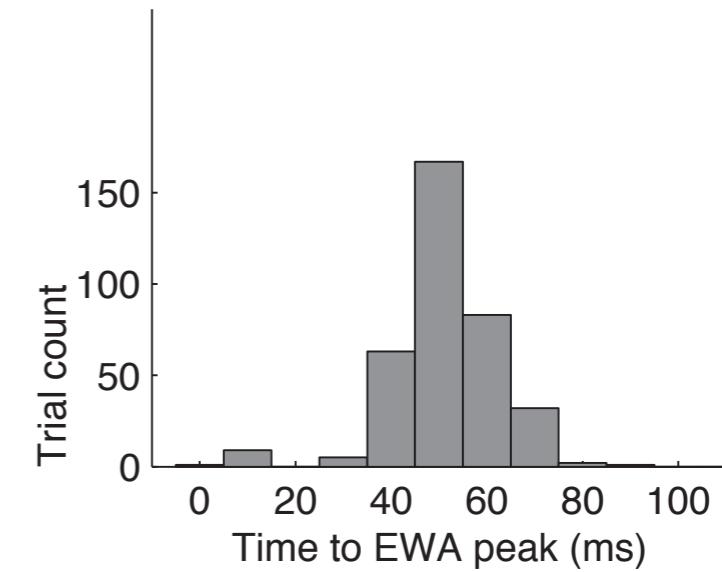
A. Normalized EMG Activity

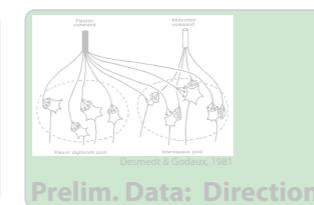
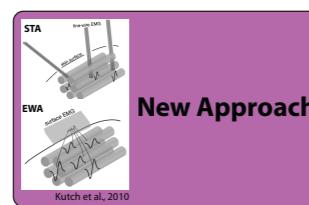


B. EWA Direction

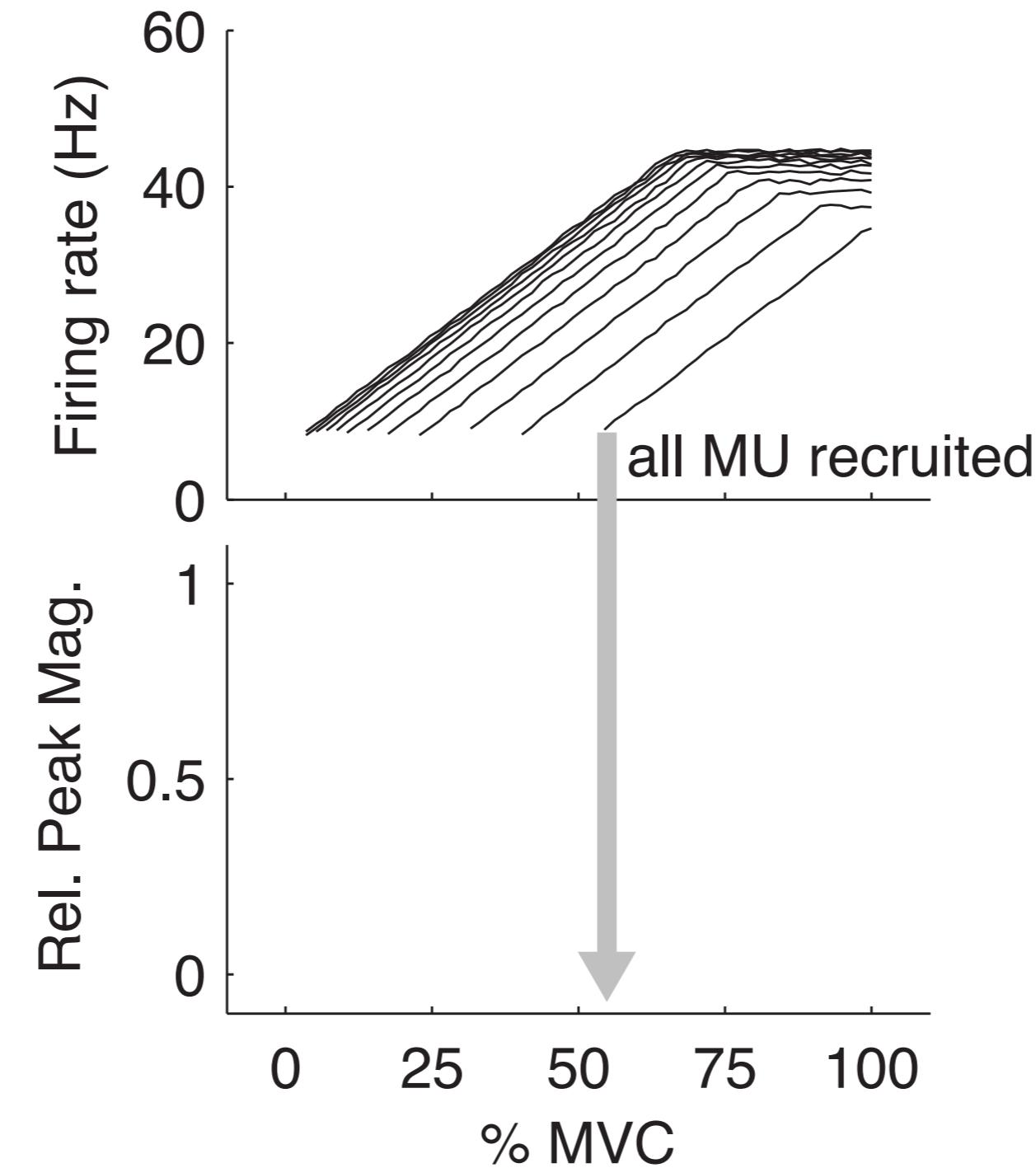


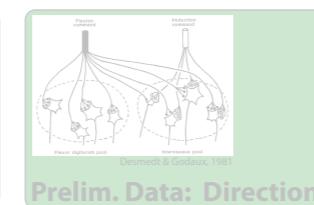
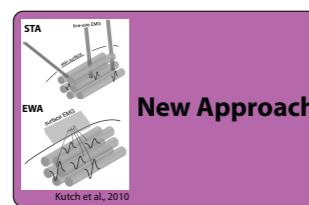
C. EWA Time-to-peak



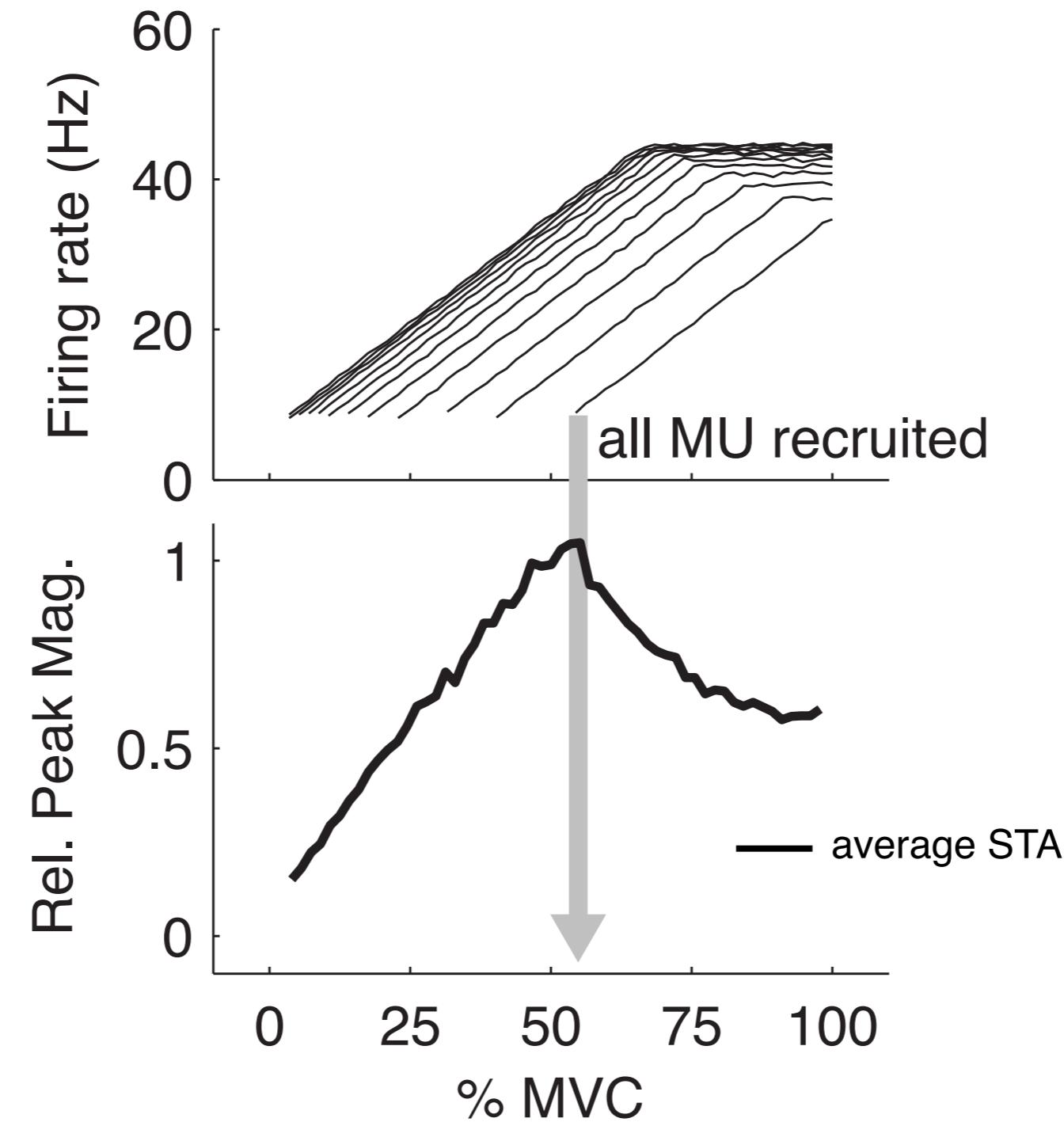


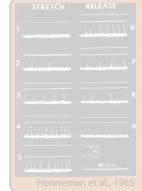
EWA shows the balance of recruitment and rate modulation





EWA shows the balance of recruitment and rate modulation

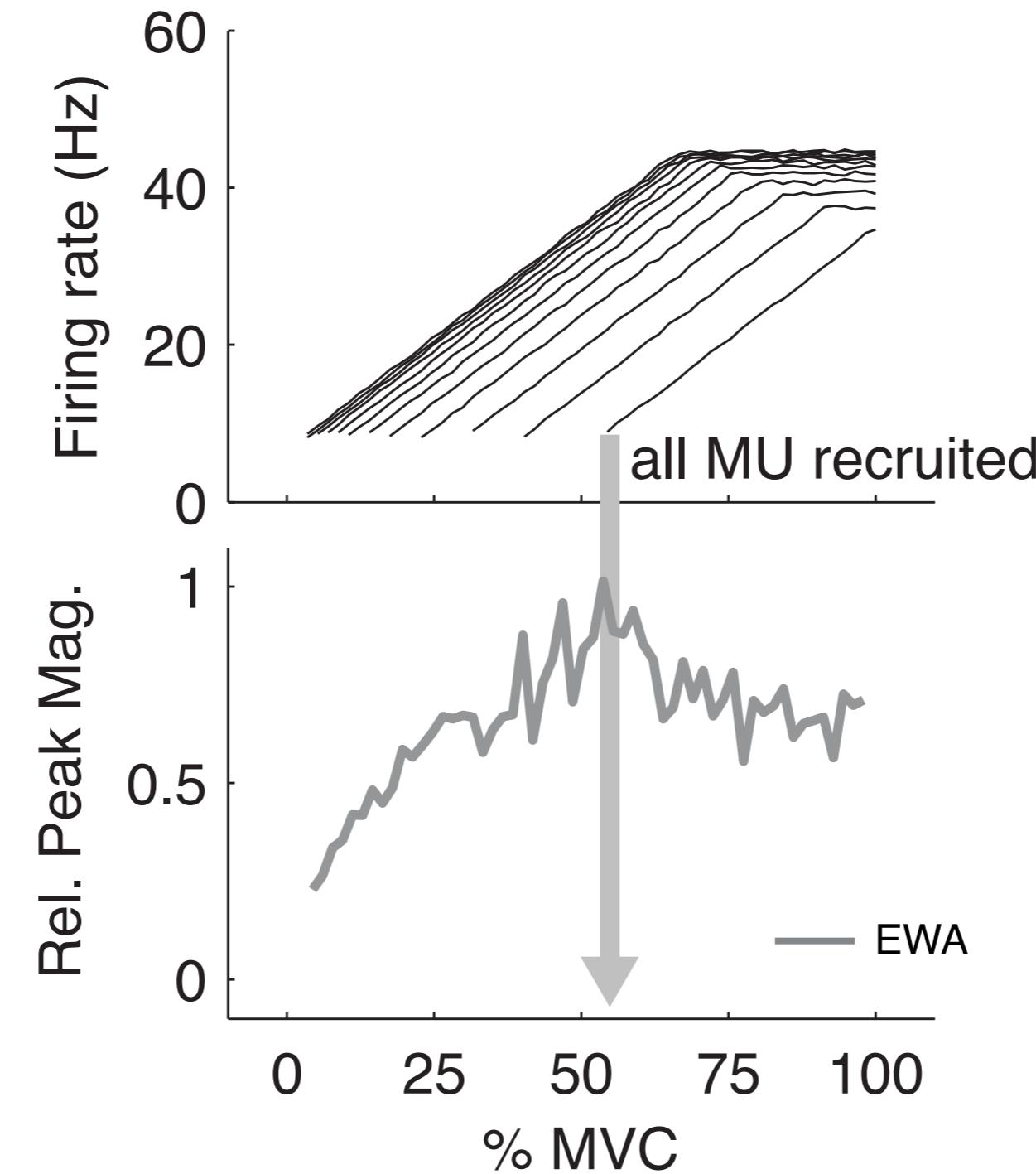


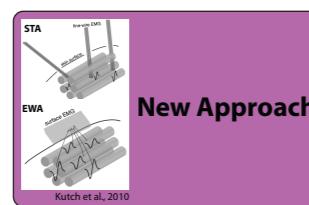


Background

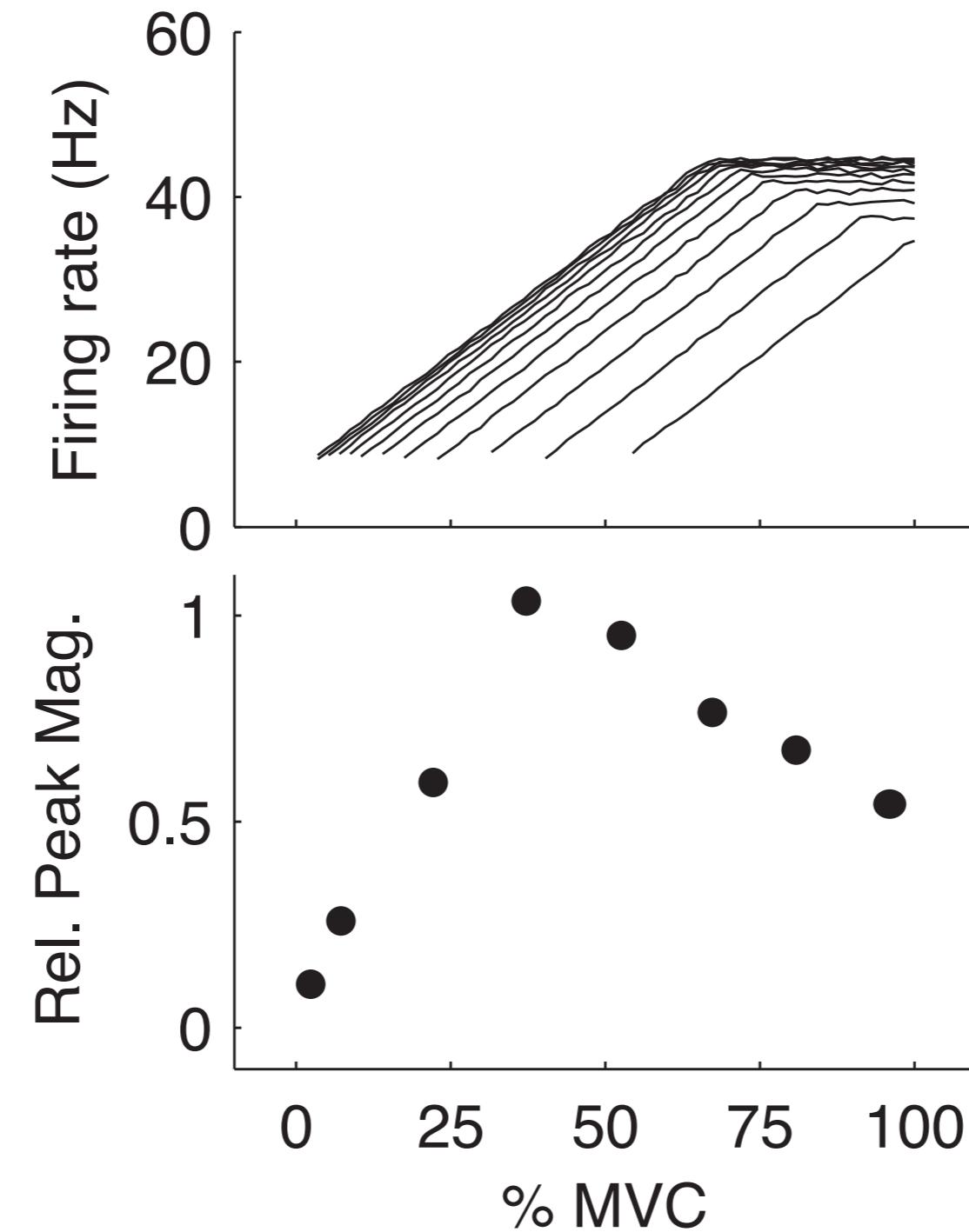


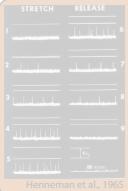
EWA shows the balance of recruitment and rate modulation





EWA shows the balance of recruitment and rate modulation

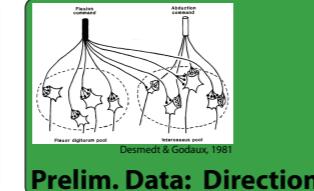




Background



New Approach



Prelim. Data: Direction



Prelim. Data: Stroke

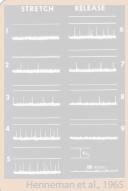
A curious paper (1981)

Spinal Motoneuron Recruitment in Man: Rank Deordering with Direction but Not with Speed of Voluntary Movement

Abstract. Single motor units in human interosseous muscle are recruited in order from small to large in slow or brisk voluntary abduction of the index finger. When the same muscle acts as a synergist as opposed to a prime mover, about 8 percent of the unit pairs consistently reversed their recruitment order. Motor commands appear to be patterned in terms of movements rather than muscles and to involve different connectivities to the motoneuron pool of a muscle executing movements in different directions.

The voluntary motor commands to a pool of spinal motoneurons can be analyzed in intact humans by recording the action potentials of single motor units with fine metal electrodes inserted through the skin (1). In graded voluntary contractions of a muscle, motor units are recruited in a stereotyped order at reproducible levels of muscle force (2). This is usually referred to as Henneman's size principle (3) because the recruitment sequence is correlated with several graded properties such as the size of the moto-

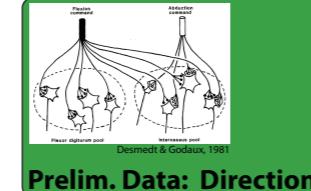
neuron and the diameter of its motor axon (4). The orderly recruitment of motor units that prevails when the muscle is used as a prime mover undergoes significant changes when the same muscle contracts as a synergist in another movement. In contrast to the concept of a fixed recruitment order, it has been occasionally reported that human subjects, when provided with visual or auditory feedback from their active motor units, can learn to voluntarily activate or suppress any arbitrarily chosen motor unit



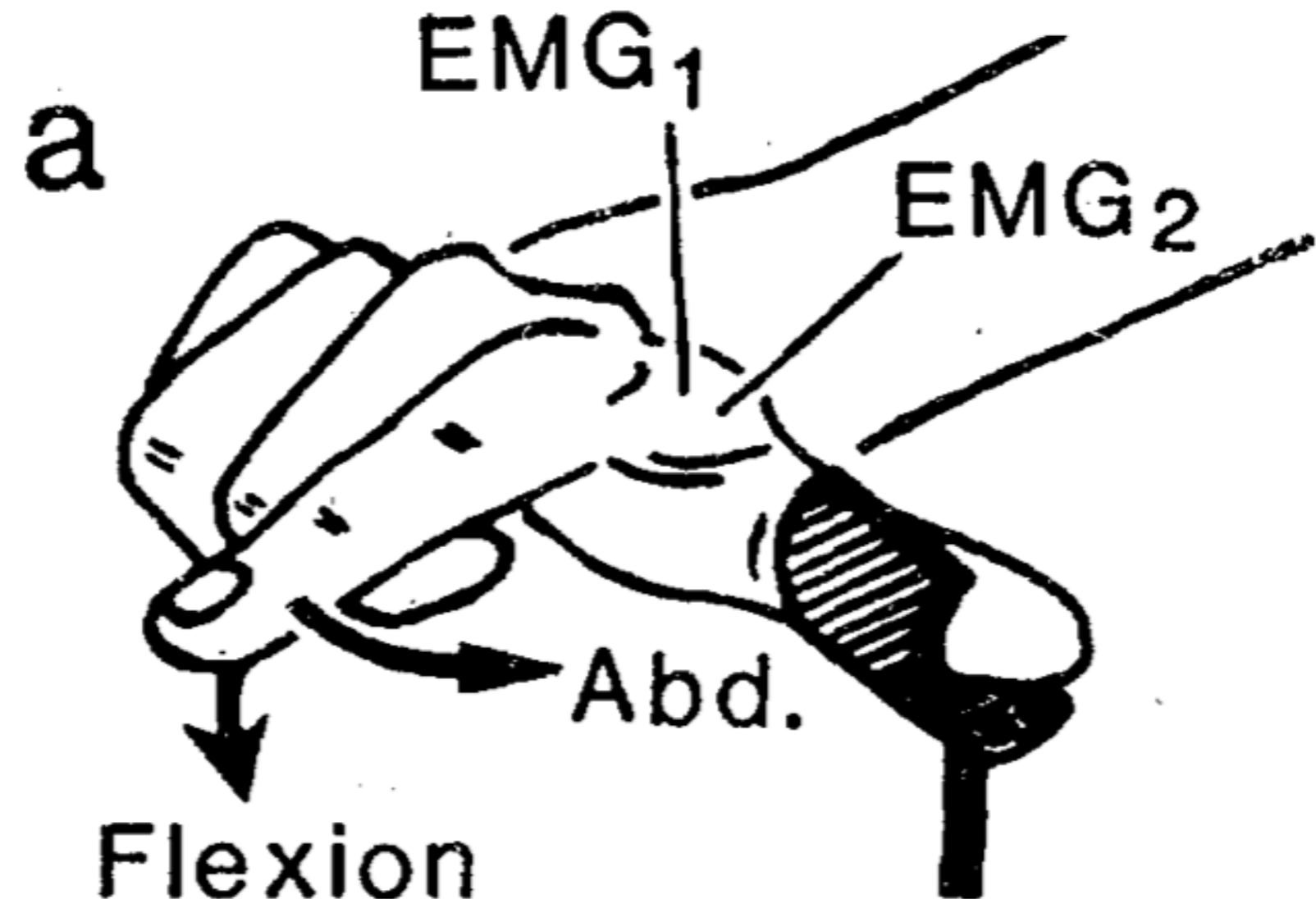
Background

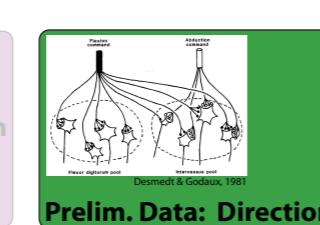


New Approach

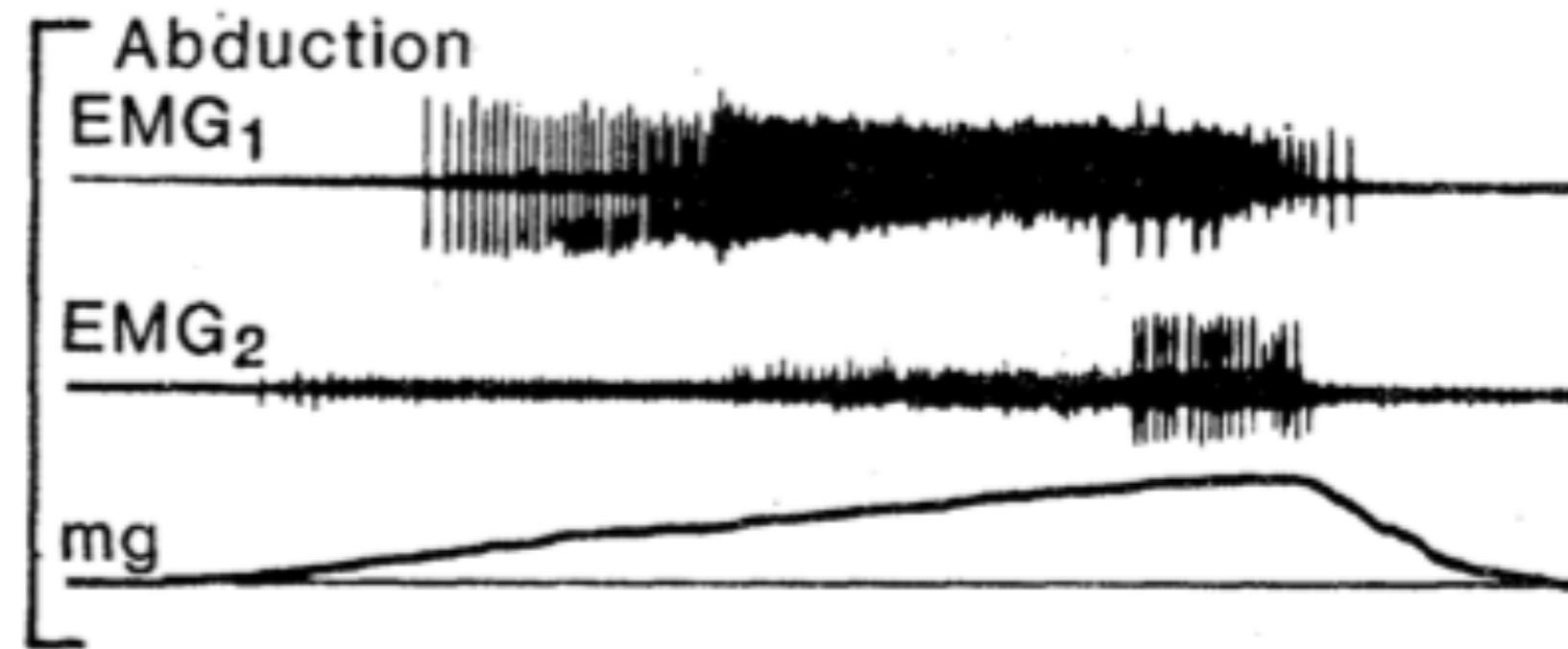


Recruitment reversals with force direction





Recruitment reversals with force direction

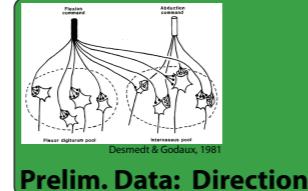




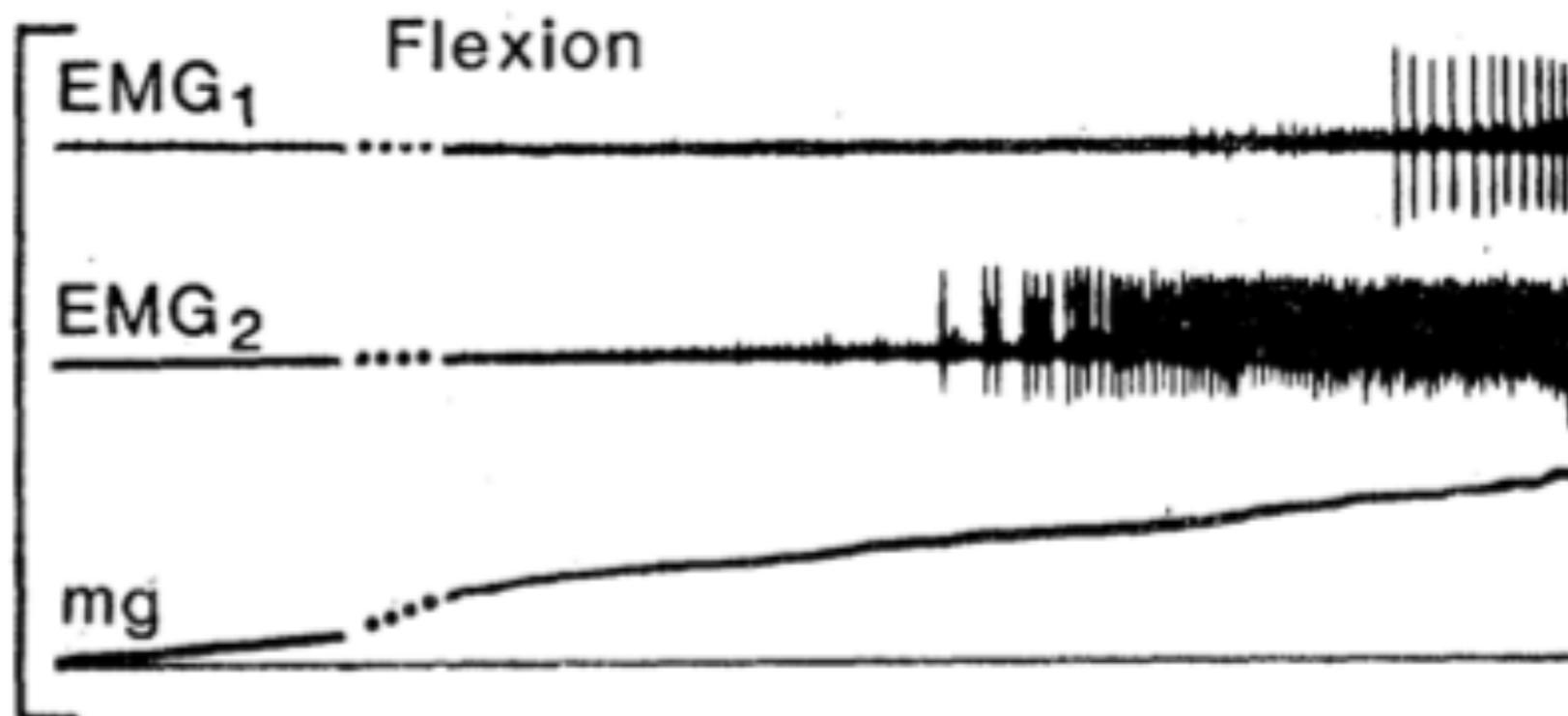
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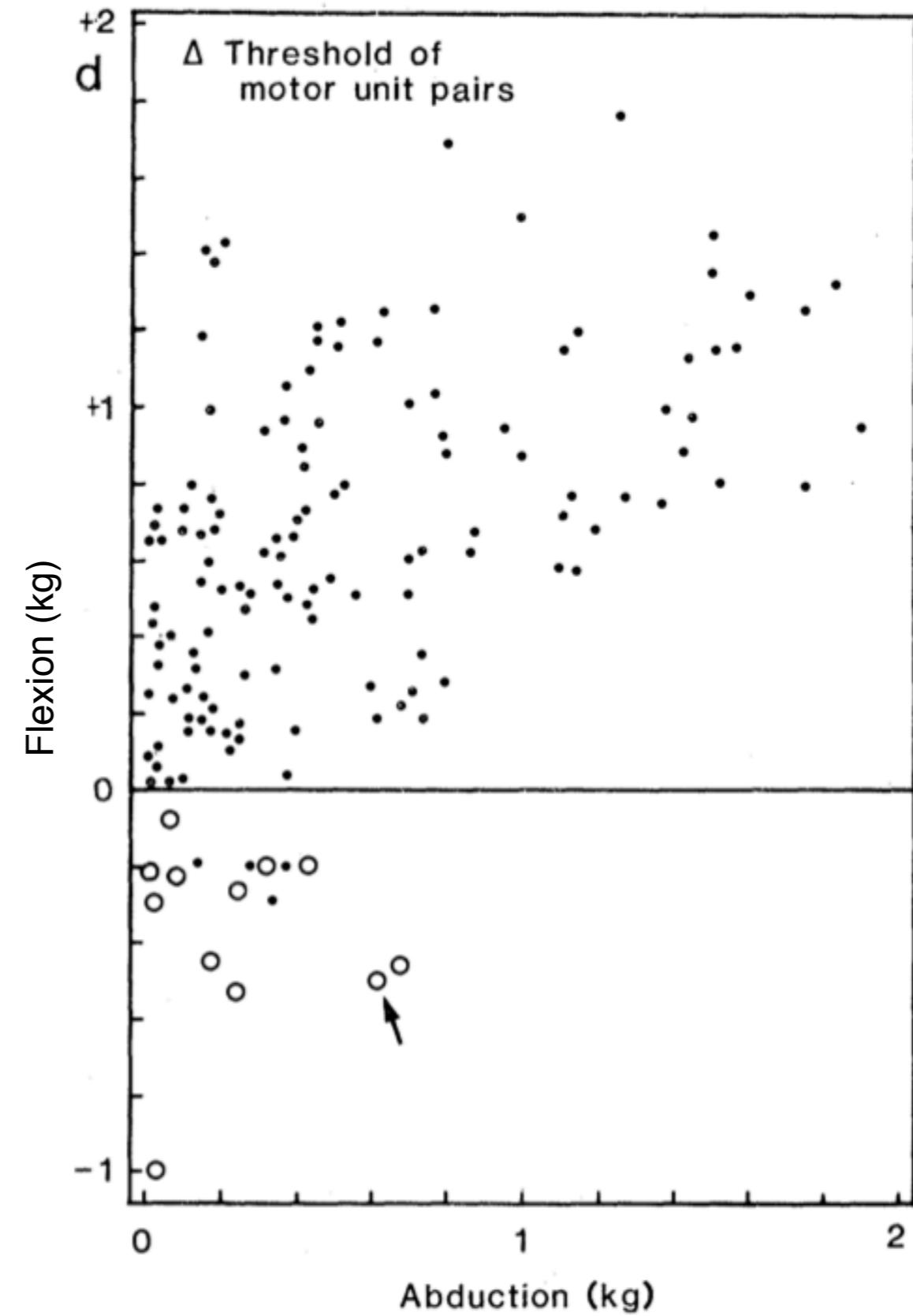


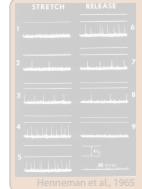
New Approach



Recruitment reversals with force direction



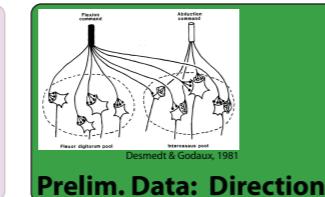




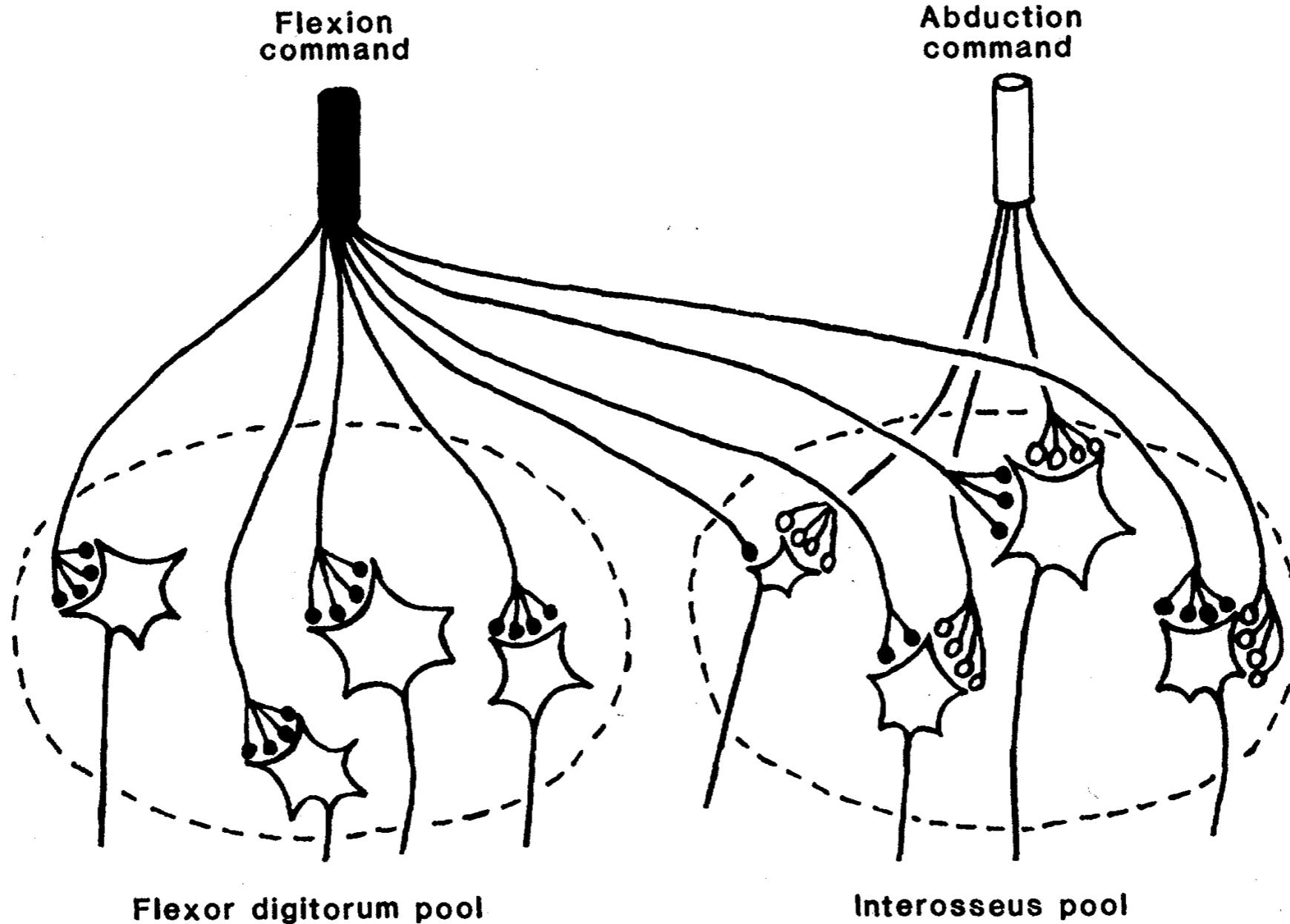
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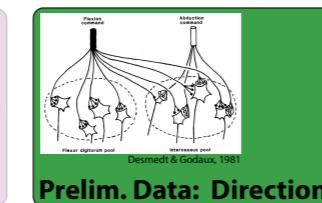
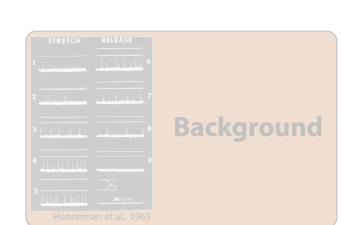


New Approach

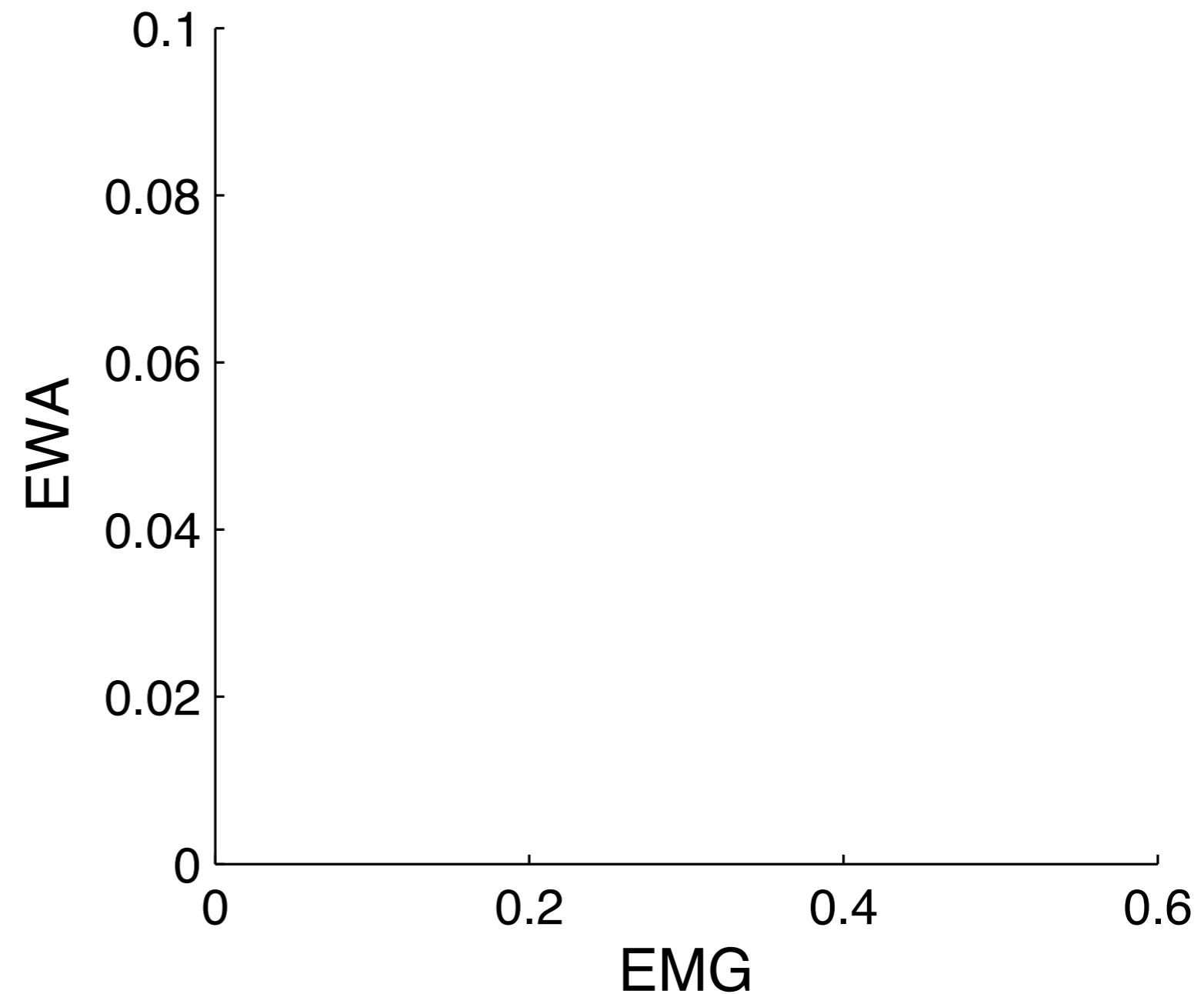
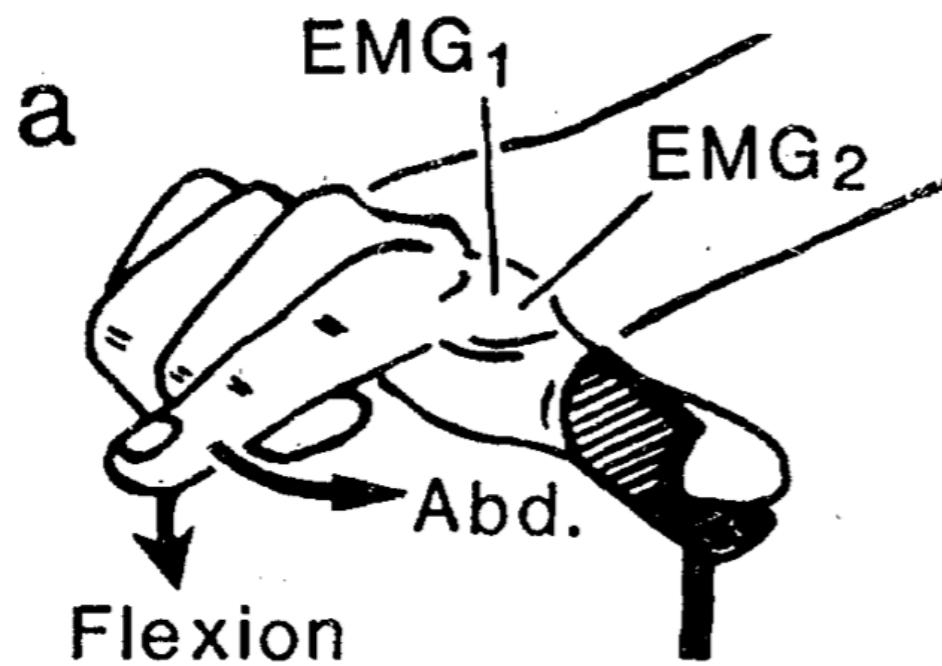


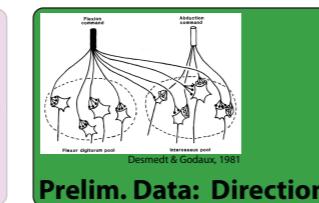
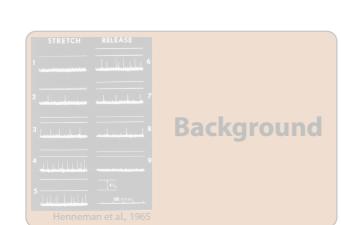
The explanation: non-uniform synaptic input



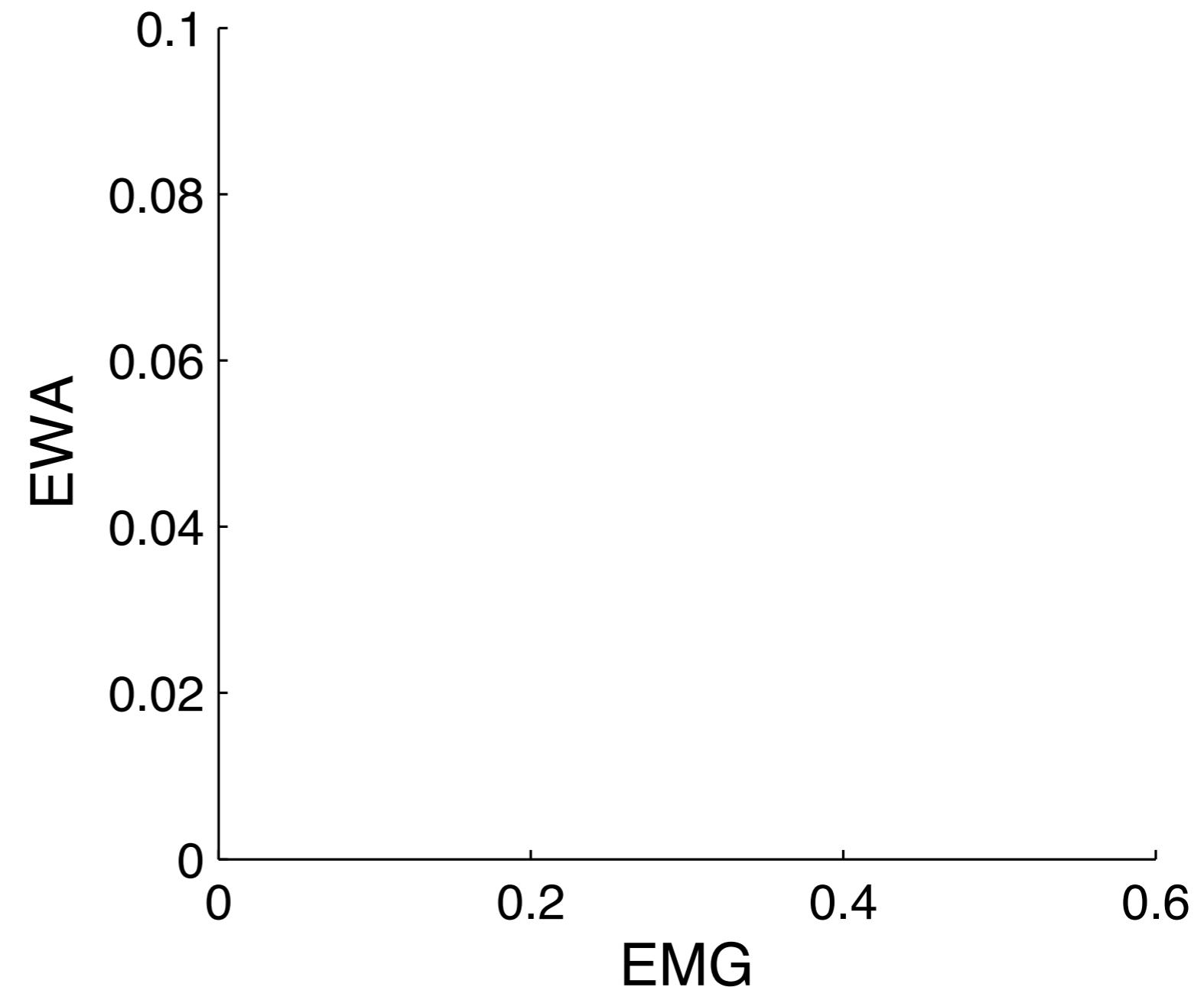
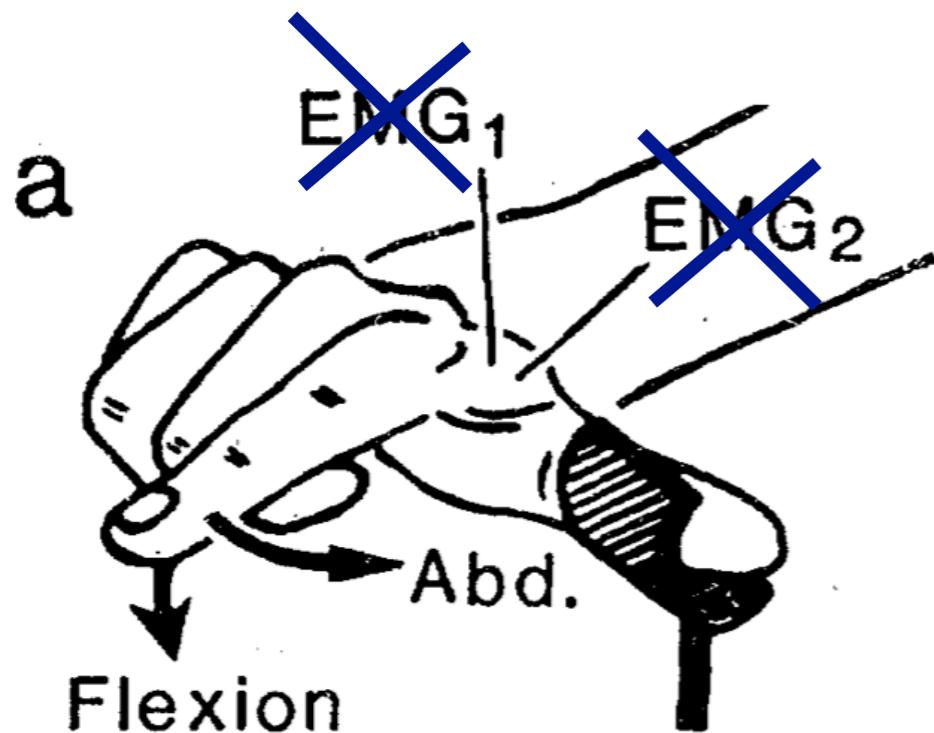


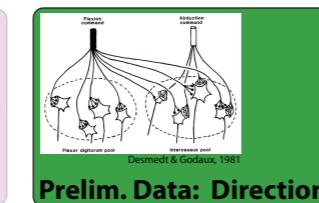
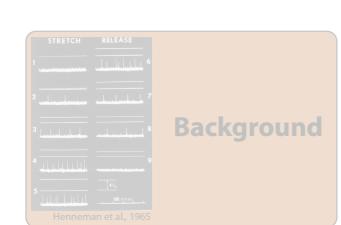
Repeating the experiment, using EWA this time



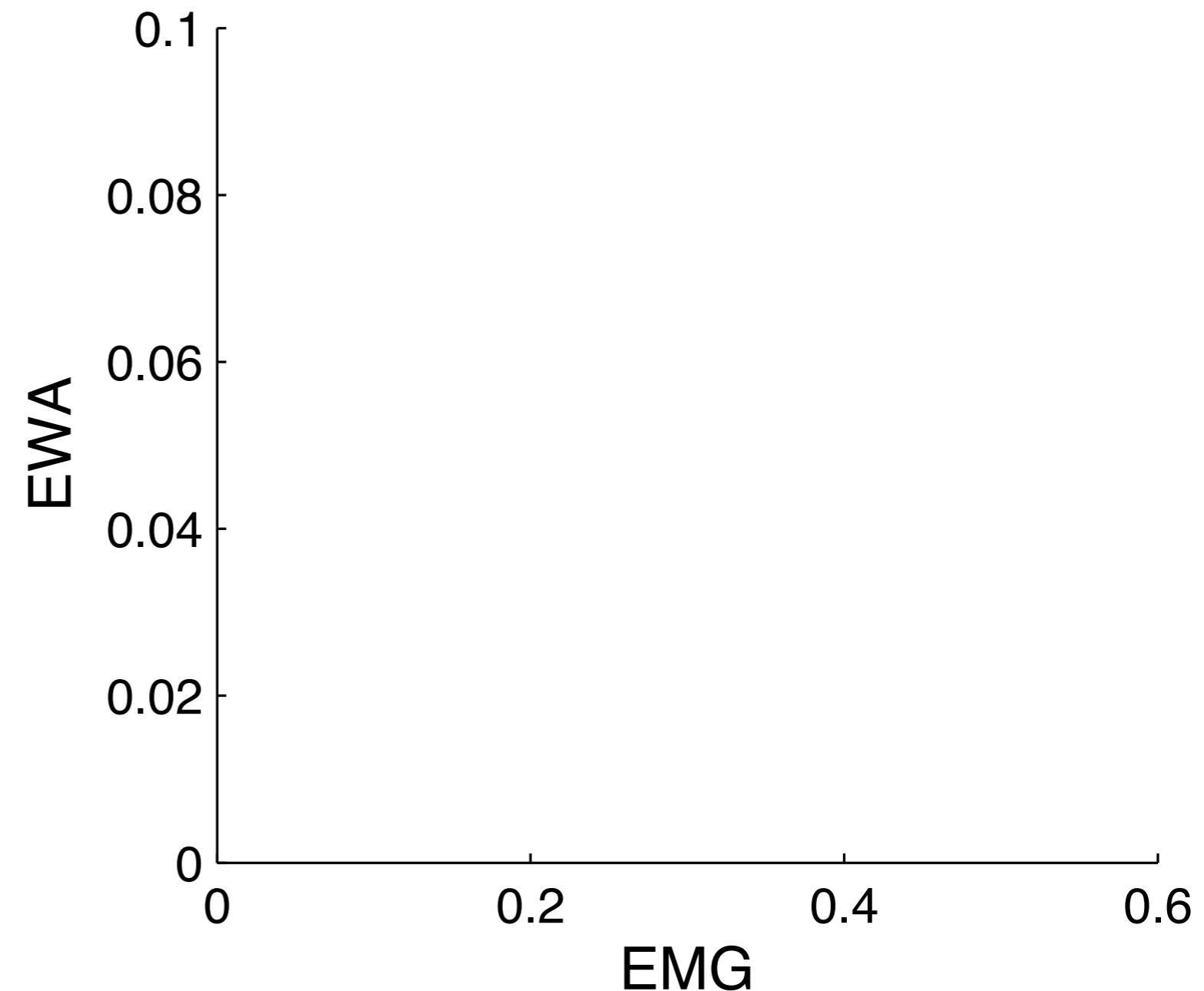
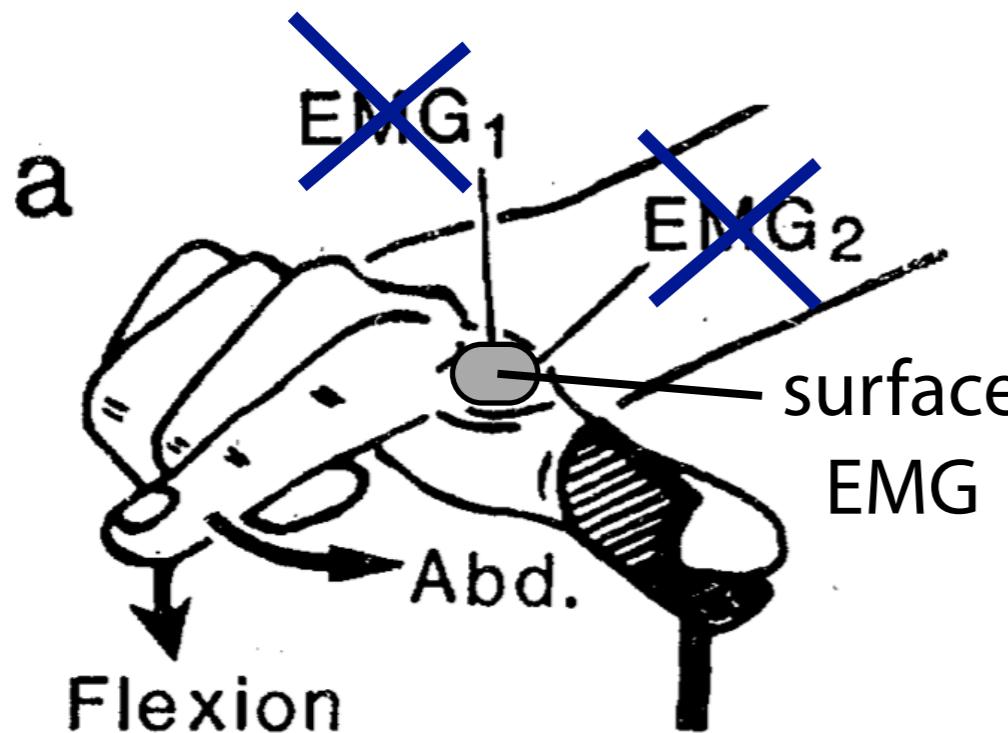


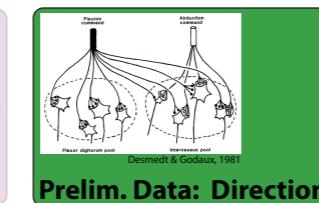
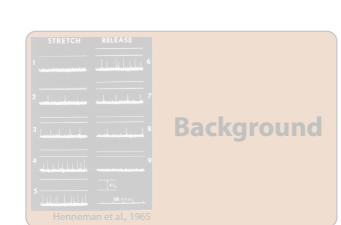
Repeating the experiment, using EWA this time



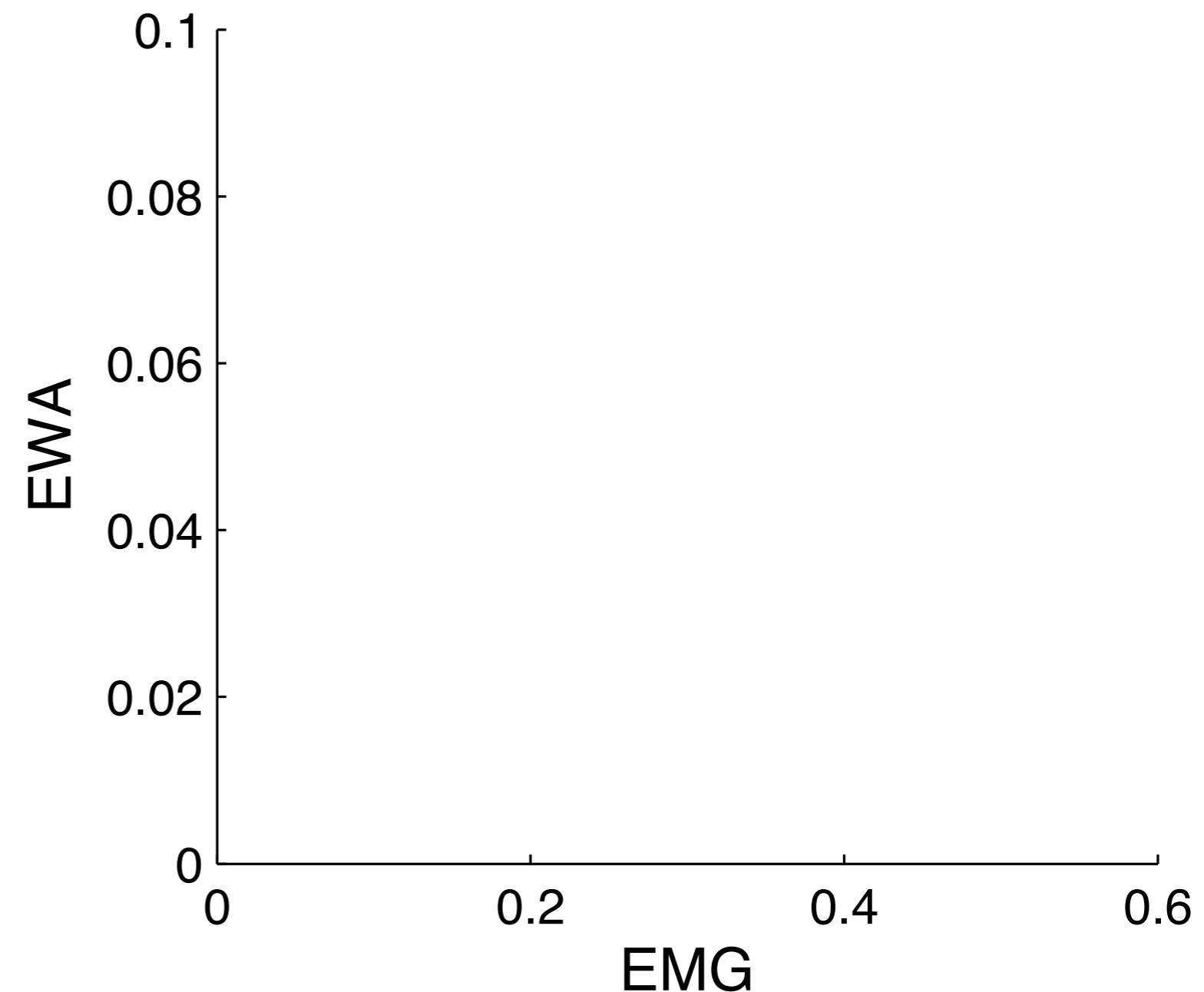
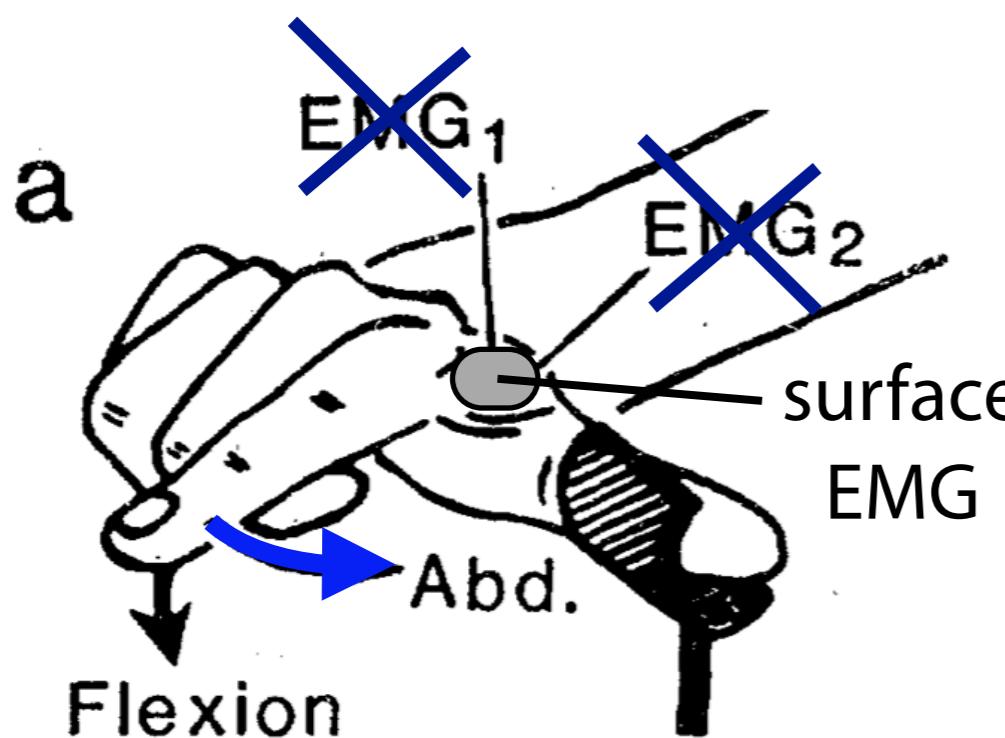


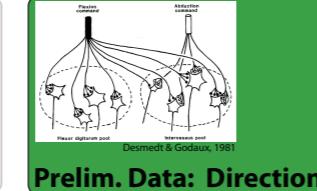
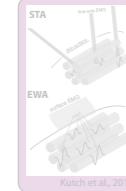
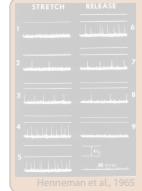
Repeating the experiment, using EWA this time



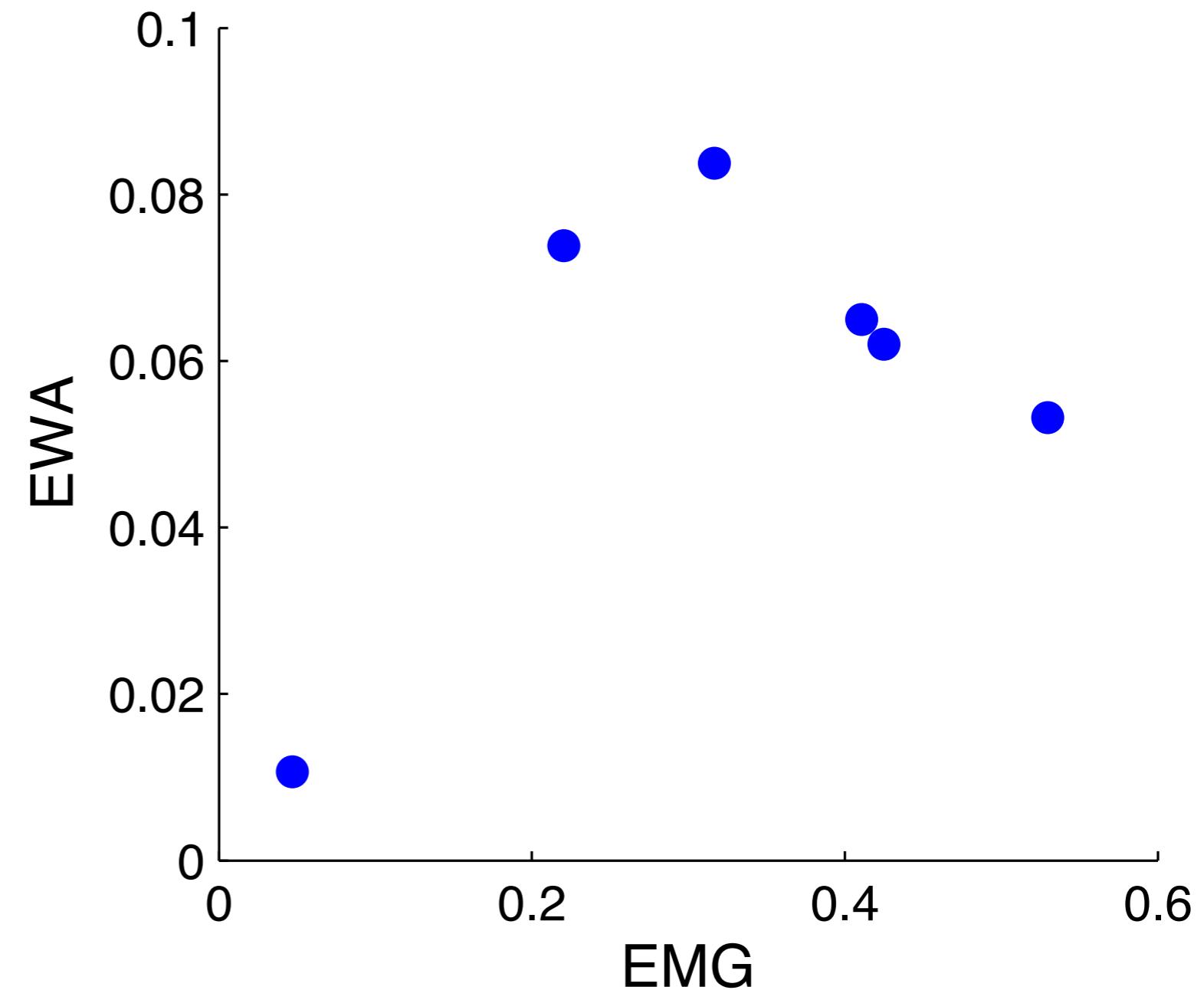
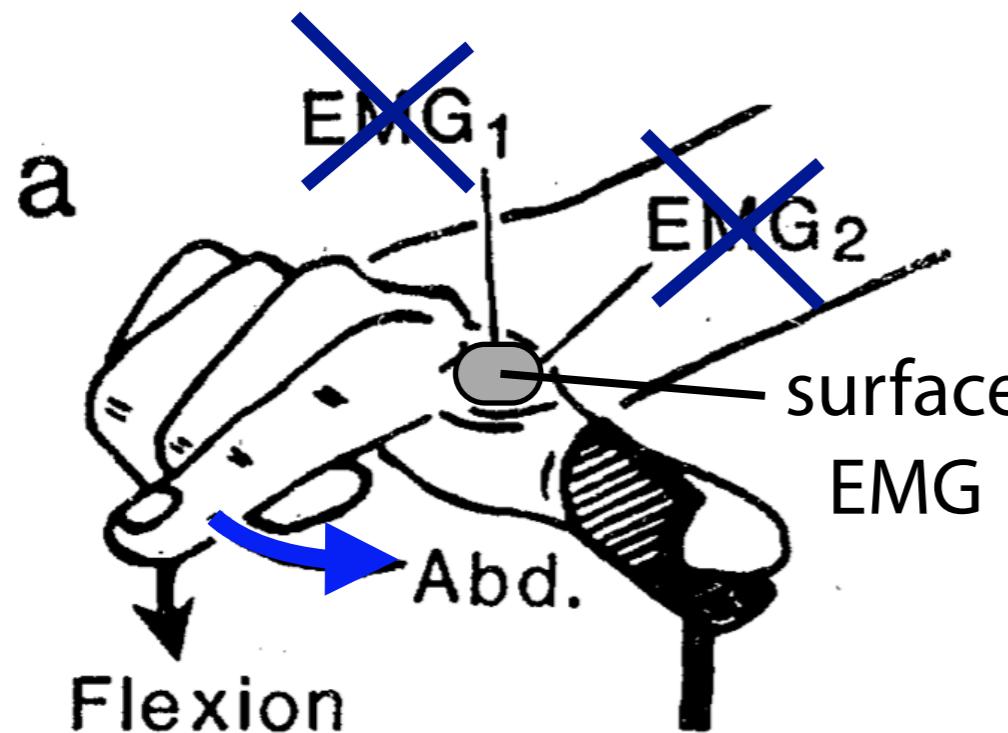


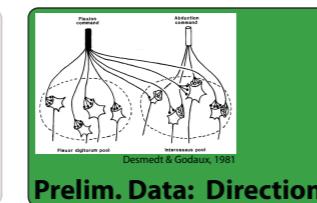
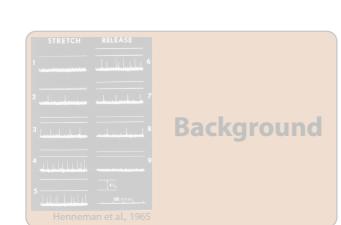
Repeating the experiment, using EWA this time



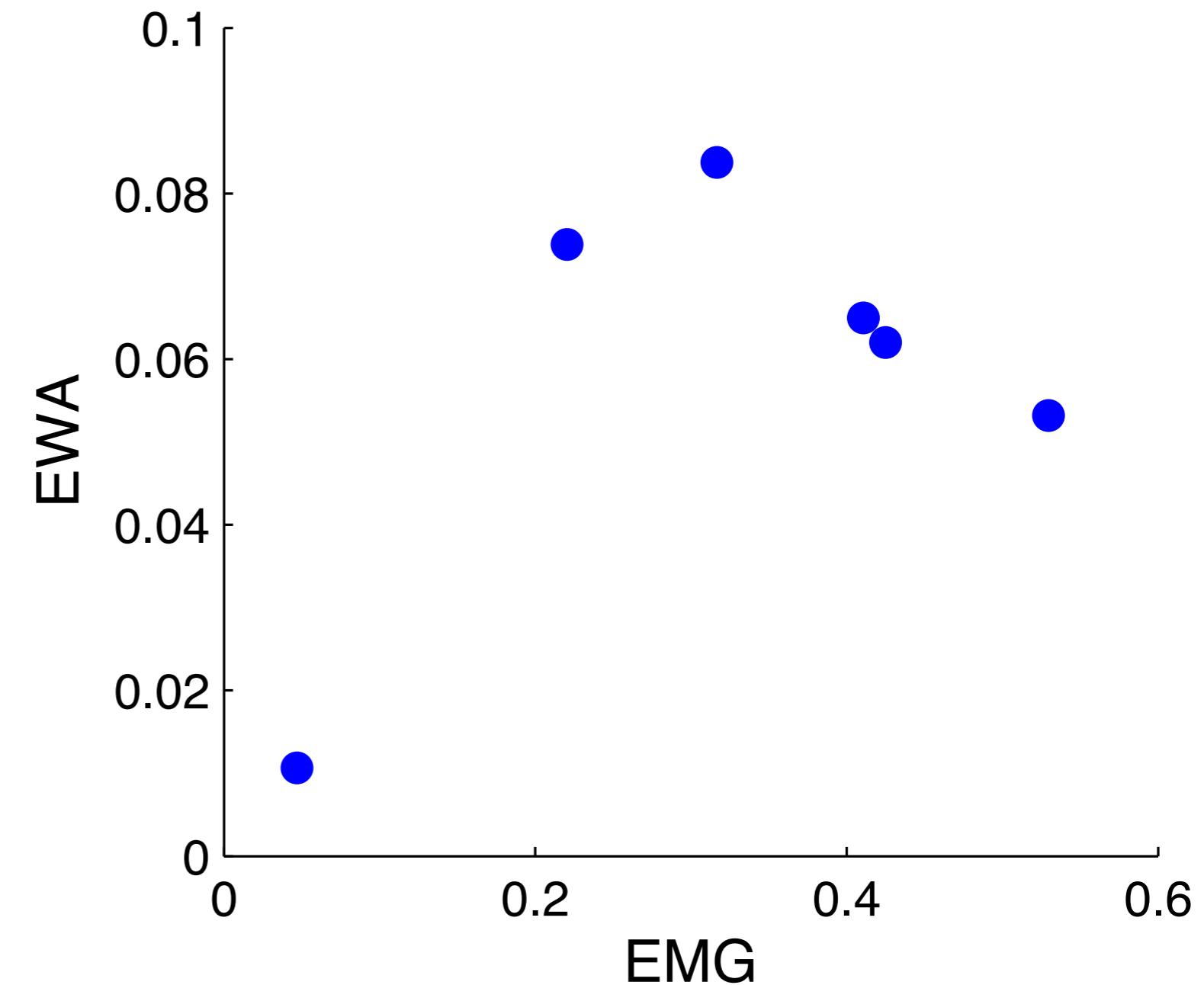
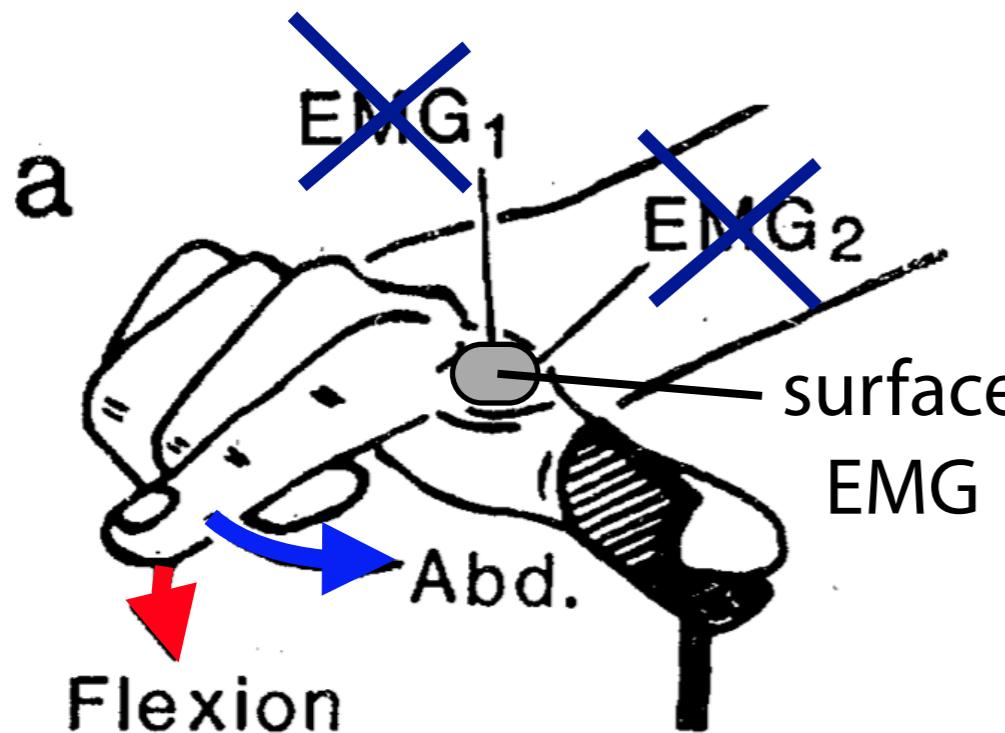


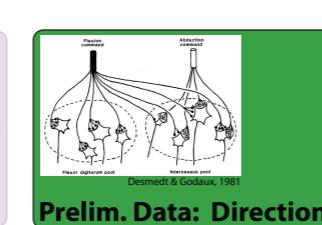
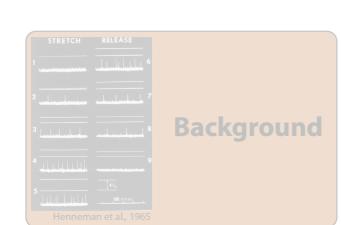
Repeating the experiment, using EWA this time



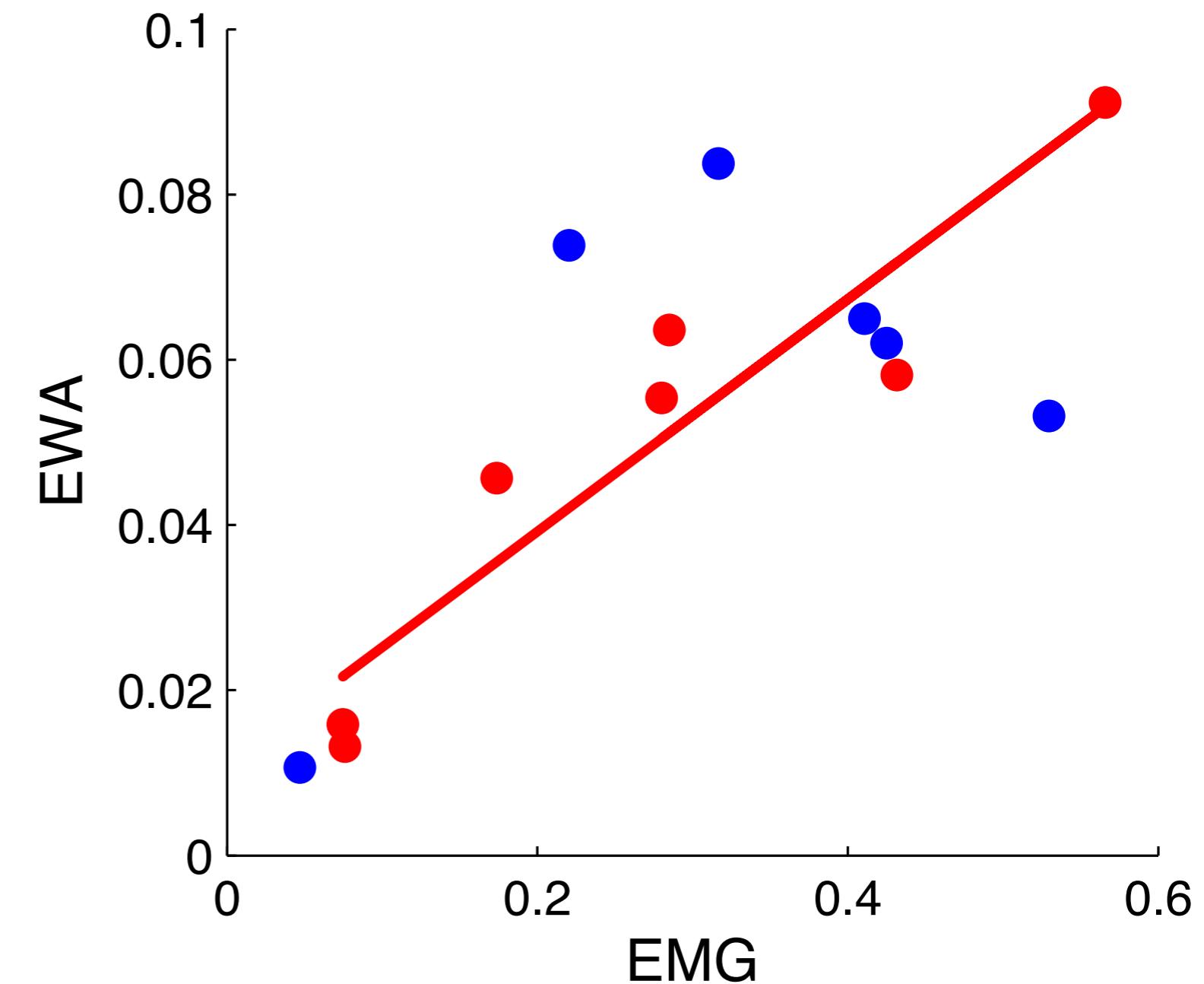
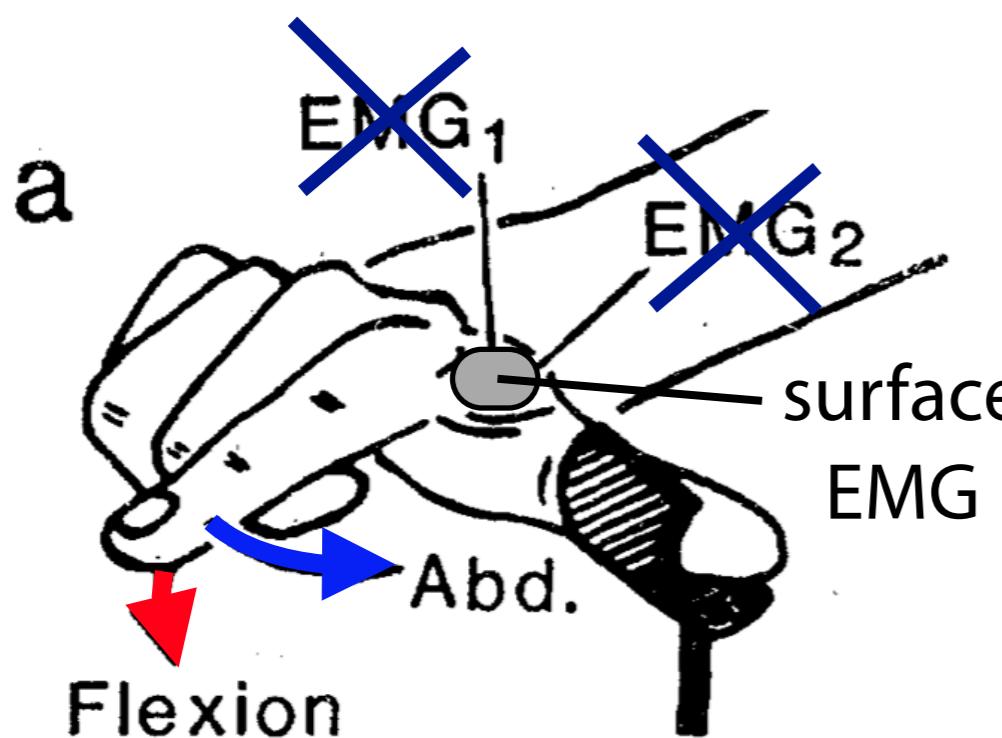


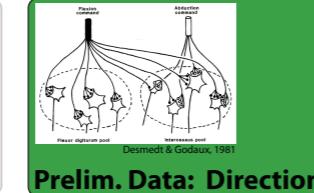
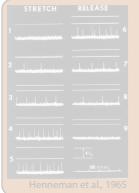
Repeating the experiment, using EWA this time



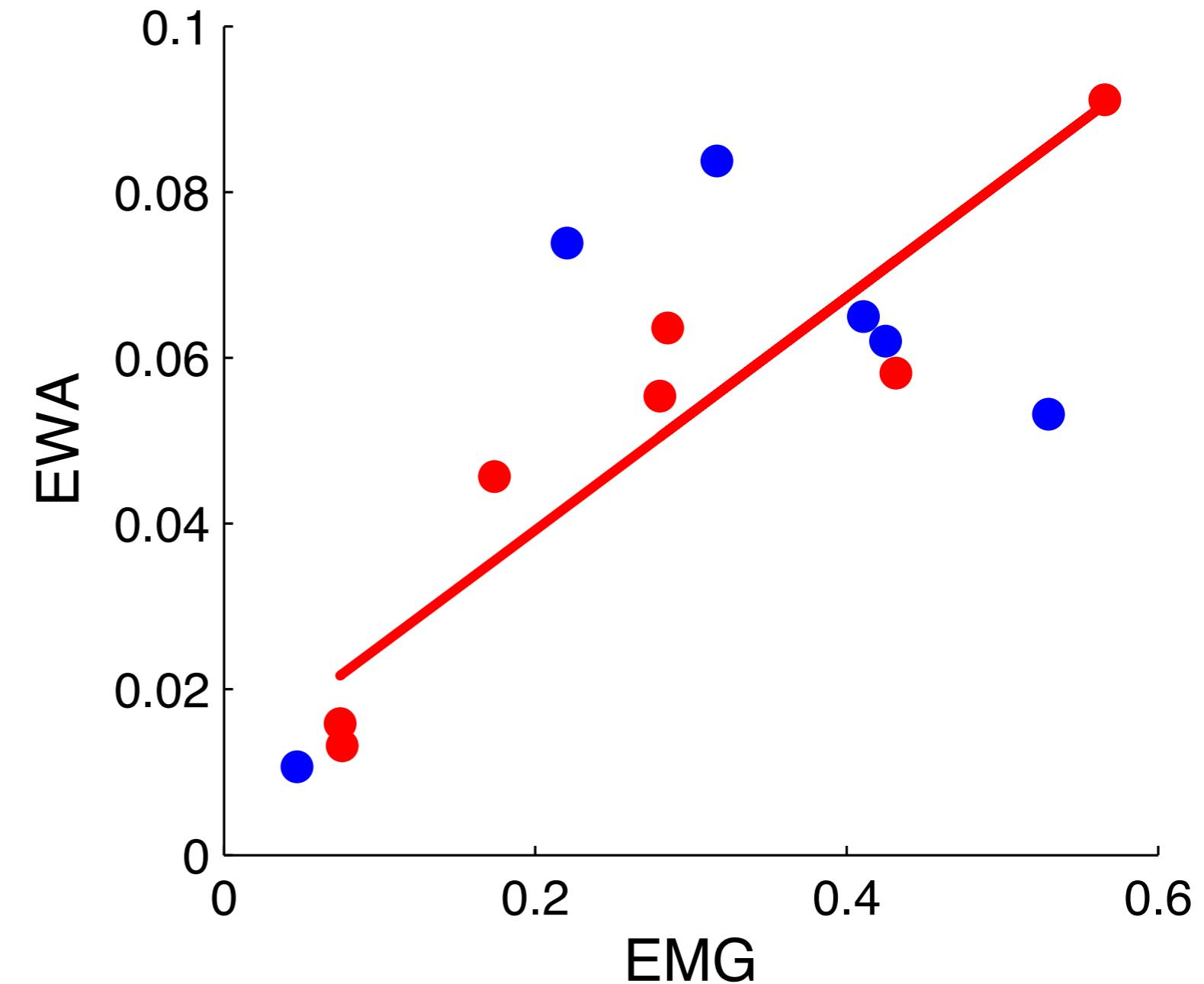
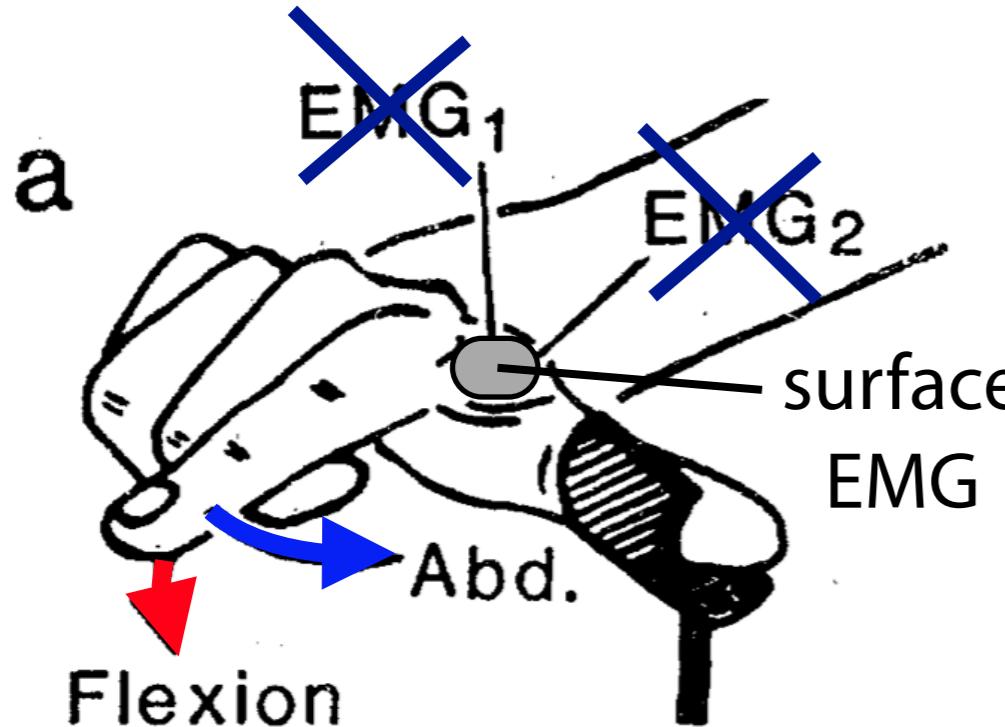


Repeating the experiment, using EWA this time





Repeating the experiment, using EWA this time



Flexion pattern: Fewer motor units firing faster

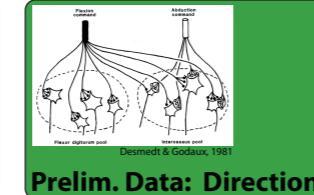
What is a synergist?



Background



New Approach

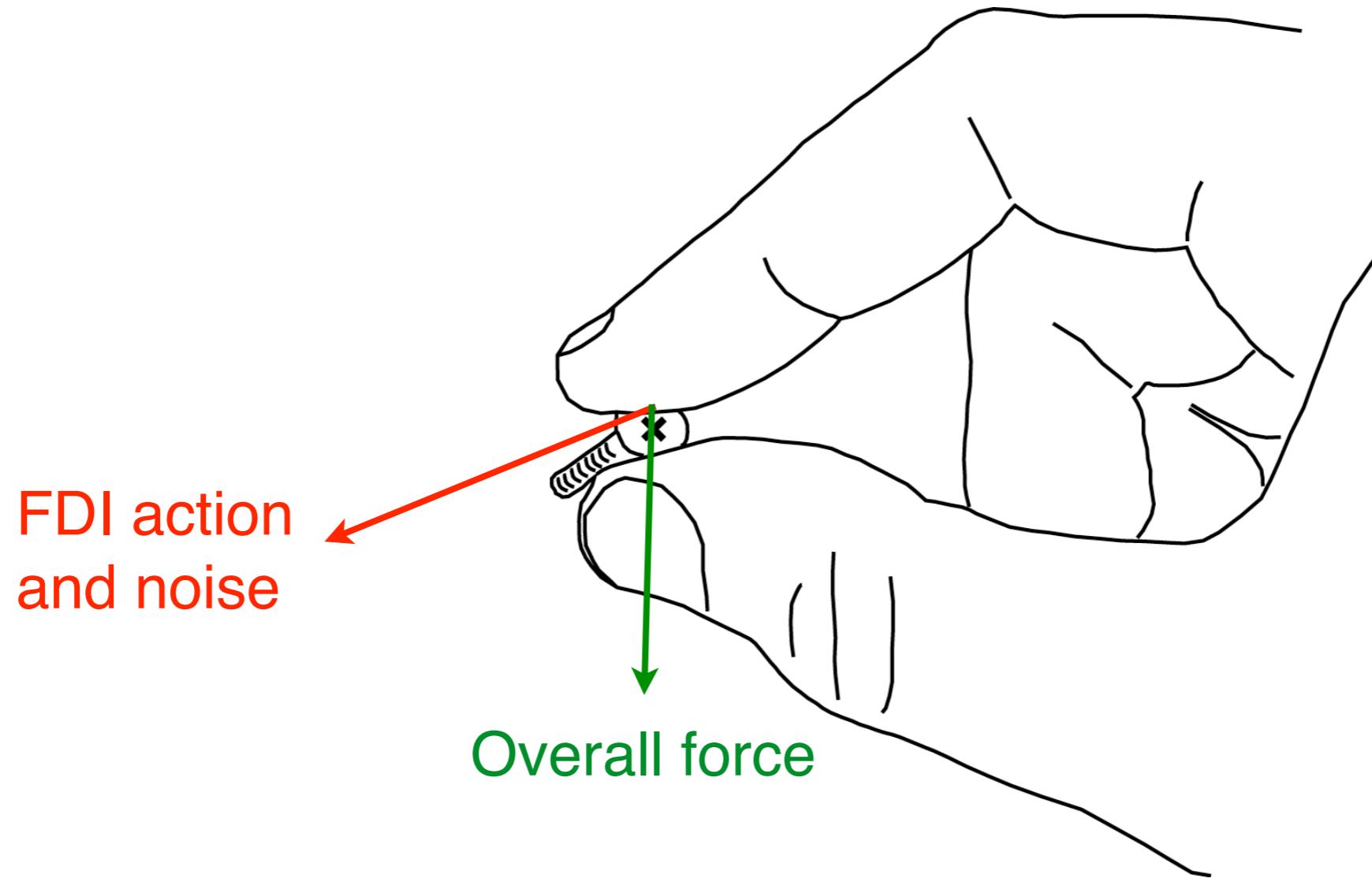


Prelim. Data: Direction



Prelim. Data: Stroke

Functional flexion



FDI action
and noise

Overall force

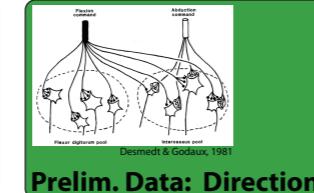
What is a synergist?



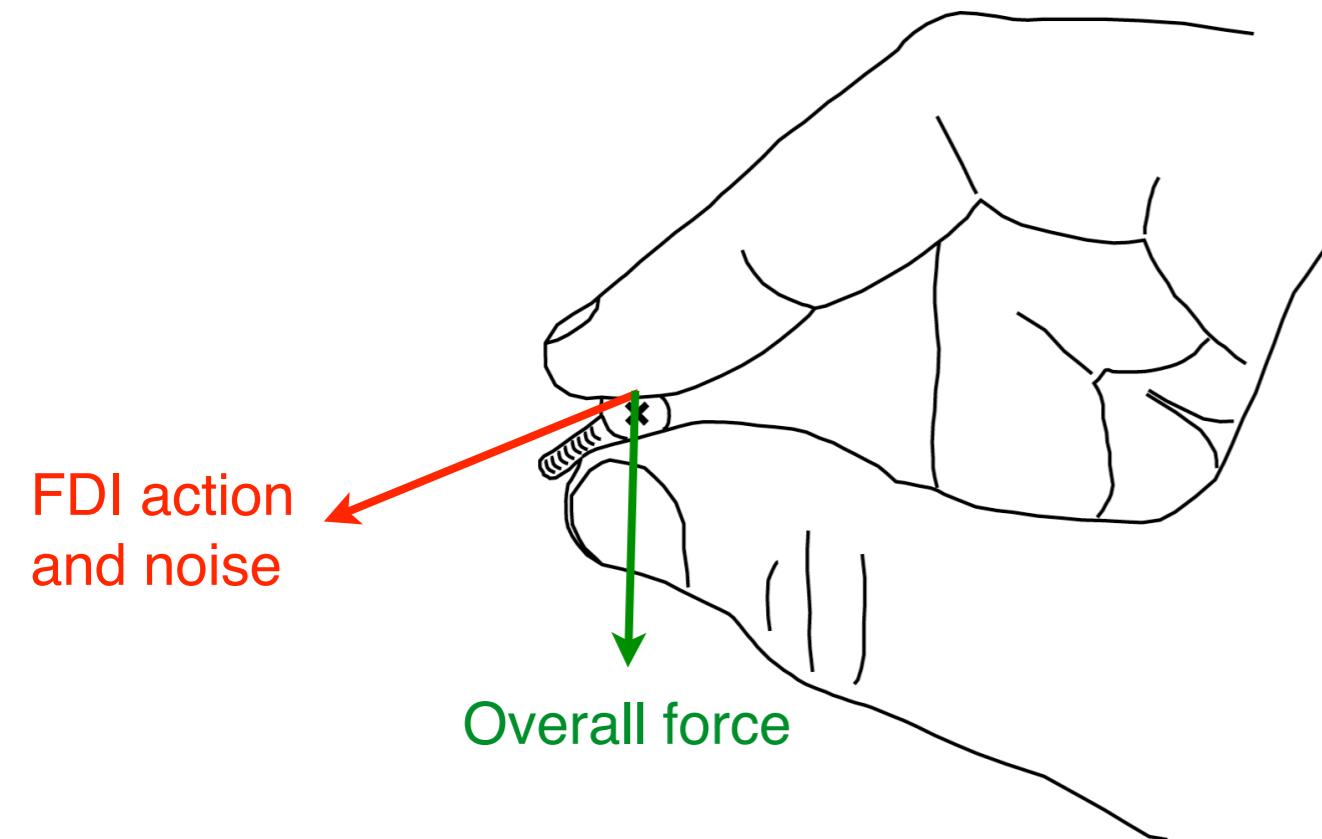
Background



New Approach



Functional flexion



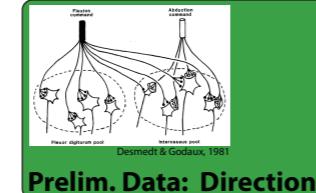
What is a synergist?



Background



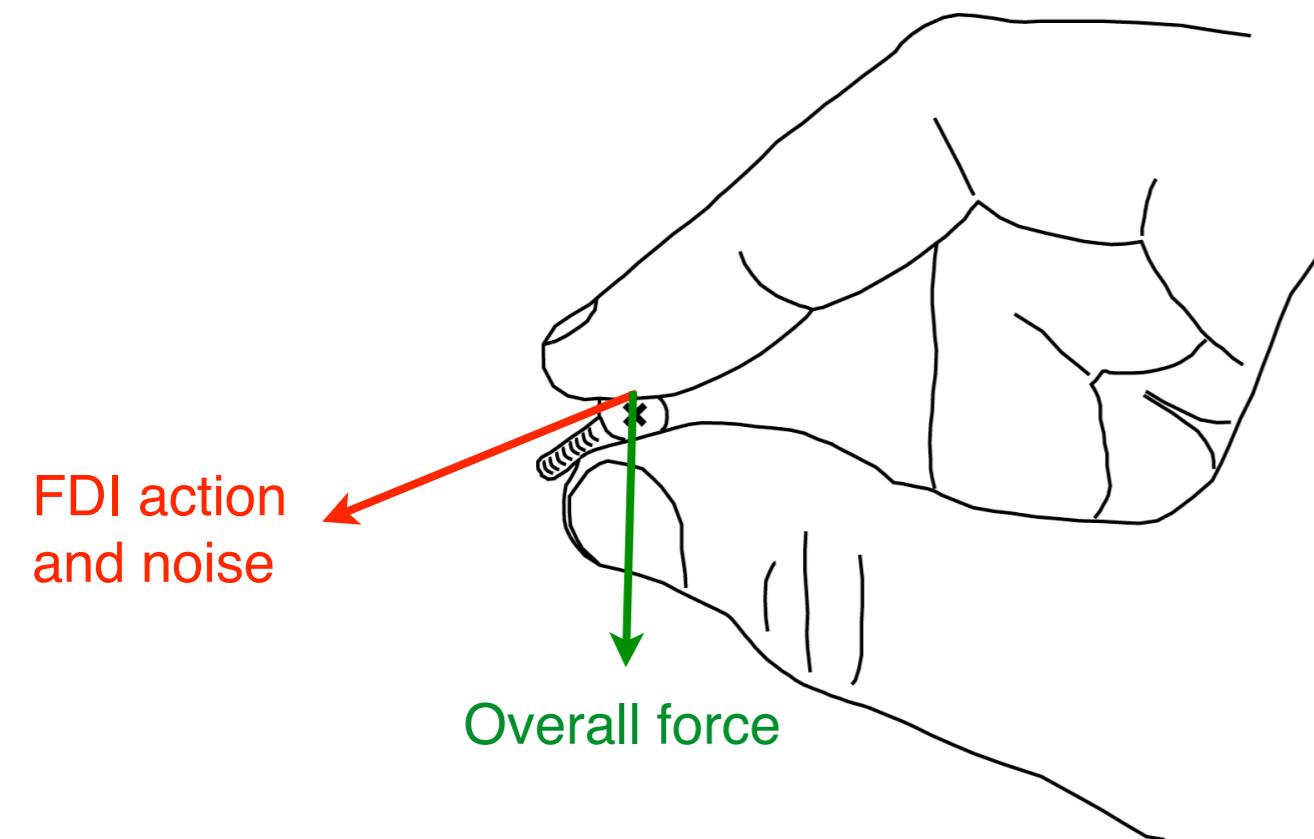
New Approach



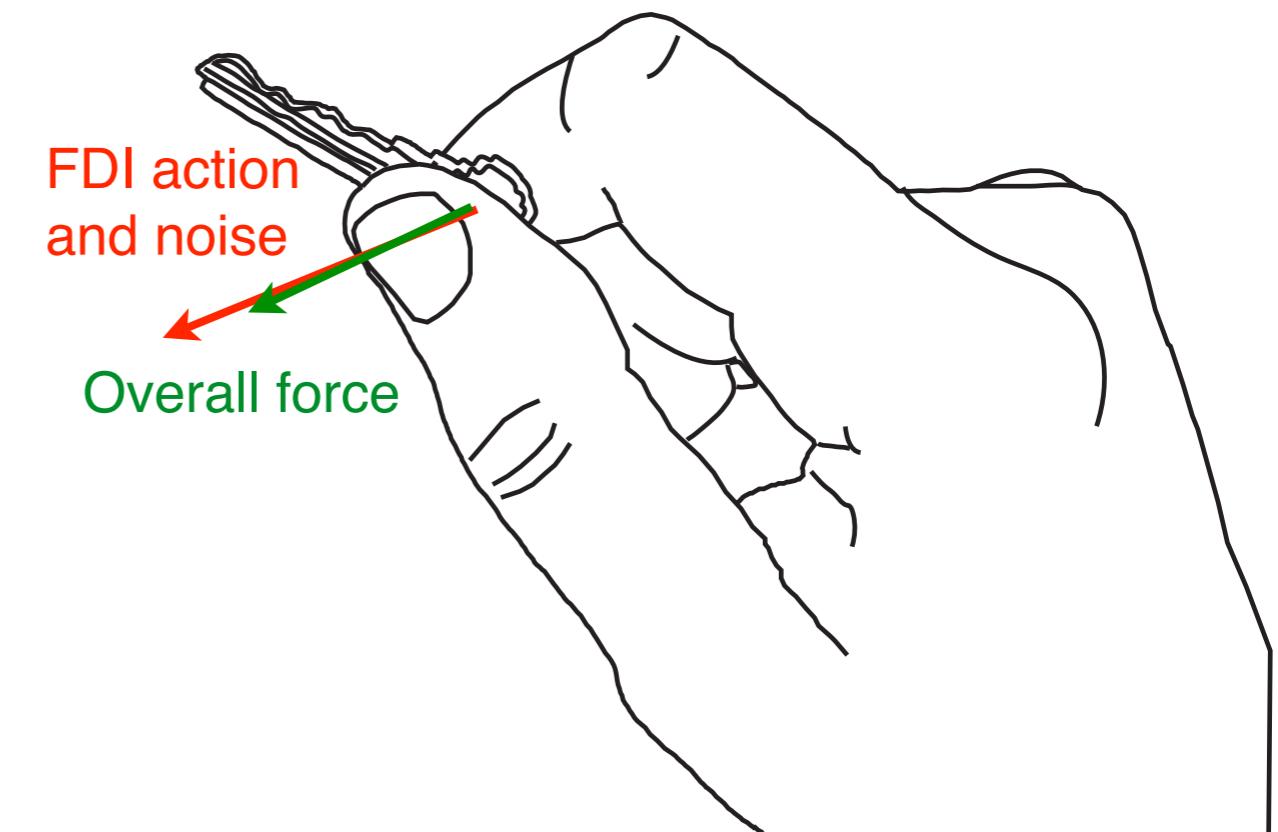
Prelim. Data: Direction

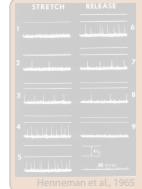


Functional flexion



Functional abduction





Background



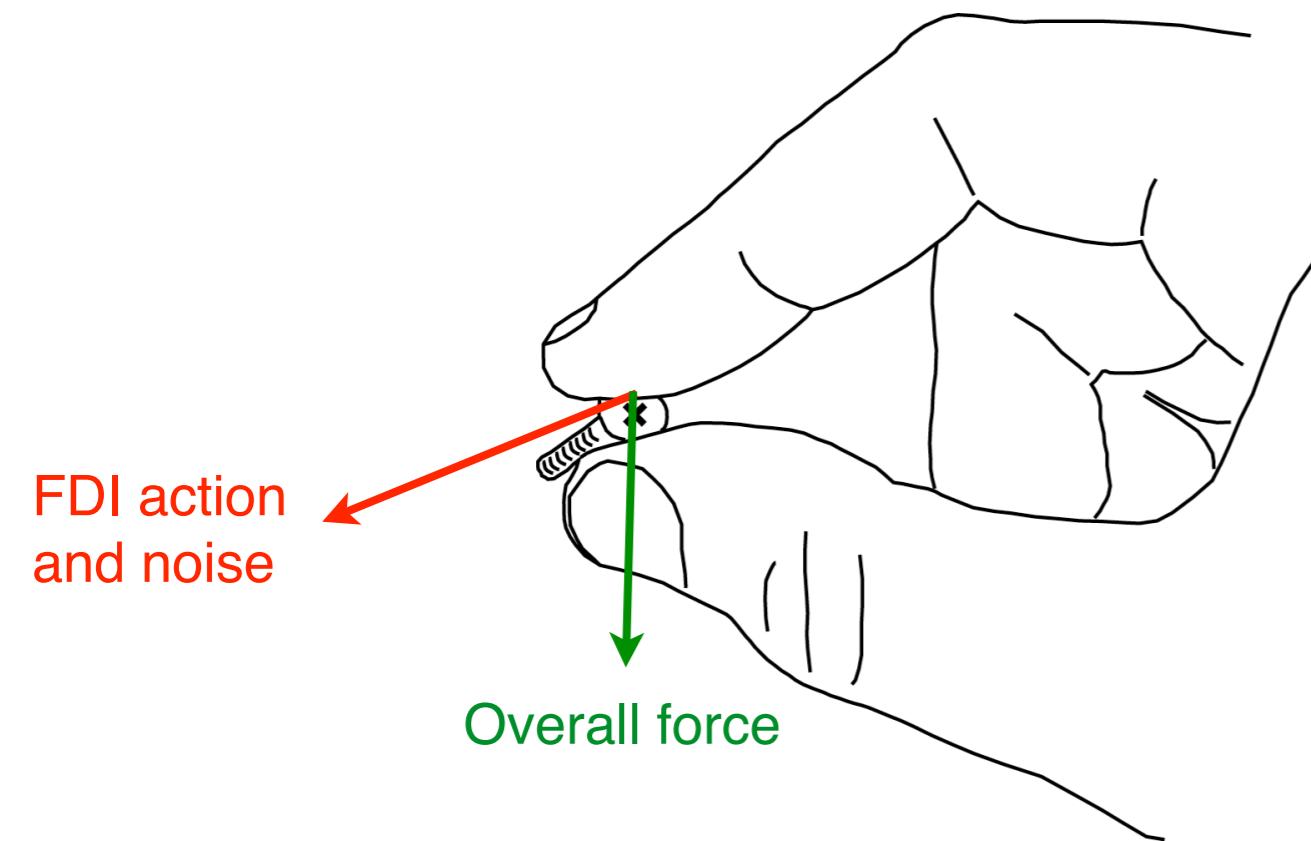
New Approach
Prelim. Data: Direction



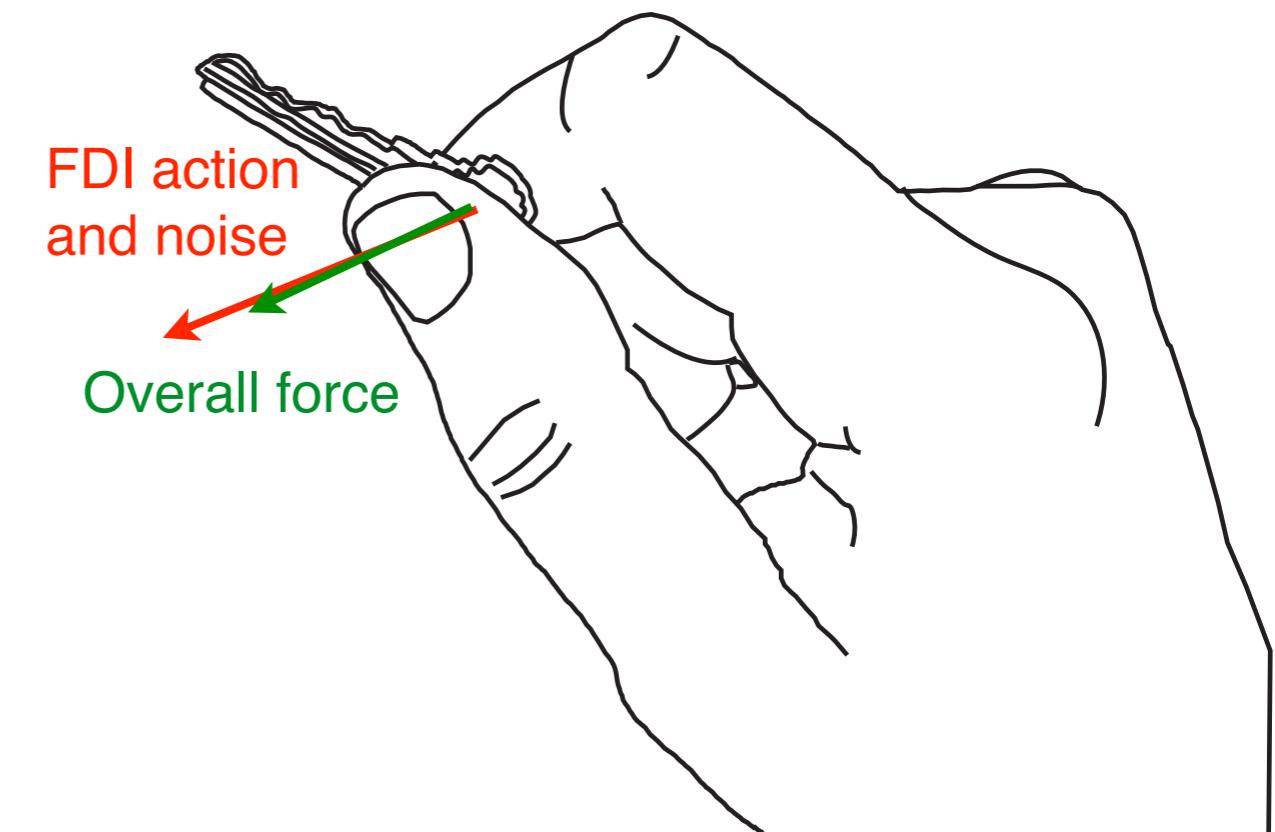
Prelim. Data: Stroke

What is a synergist?

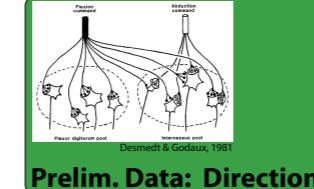
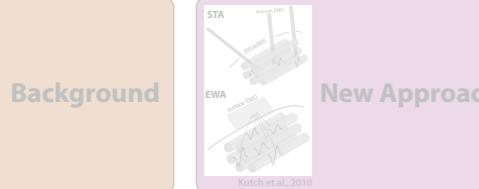
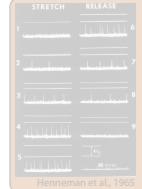
Functional flexion



Functional abduction

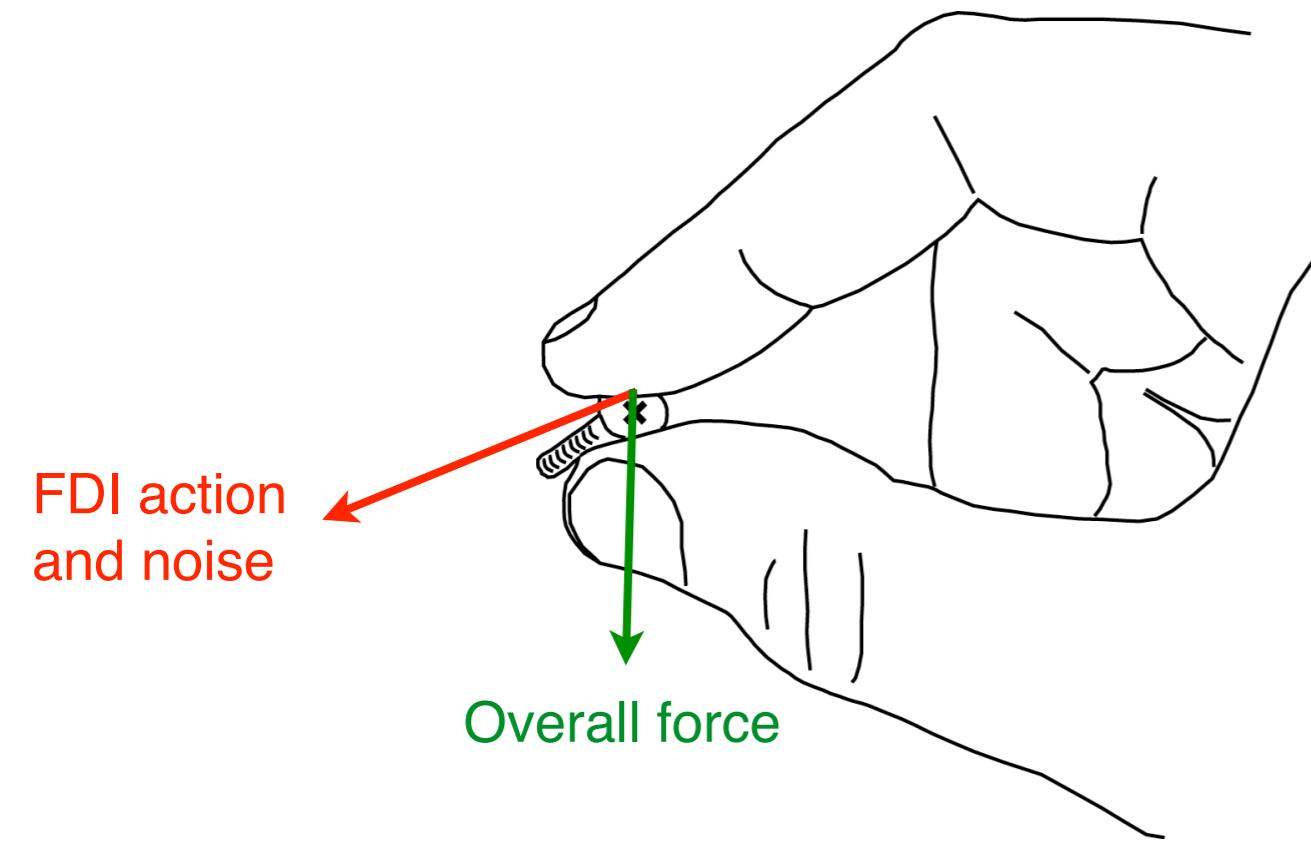


FDI SDN is perpendicular to overall force: noise is more of a problem



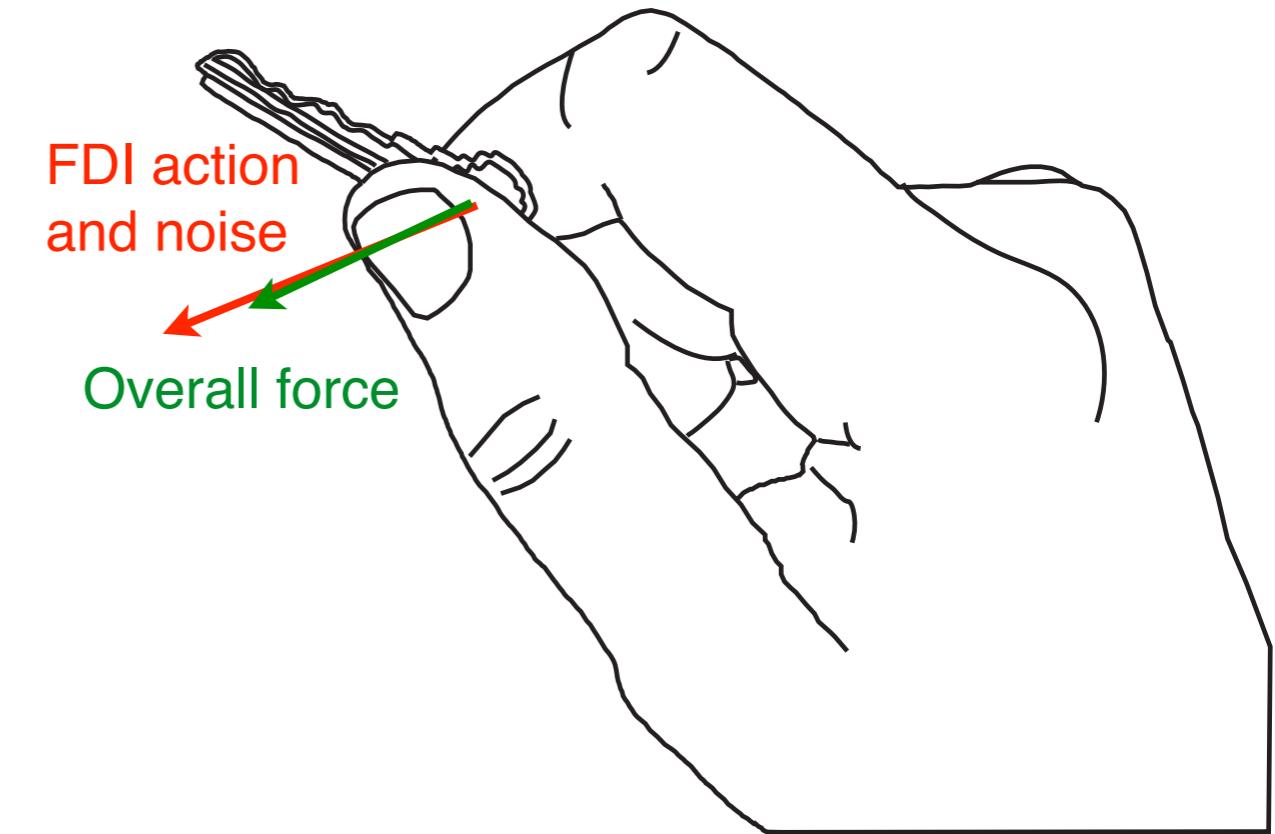
What is a synergist?

Functional flexion

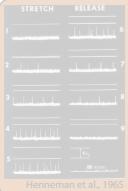


FDI SDN is perpendicular to overall force: noise is more of a problem

Functional abduction



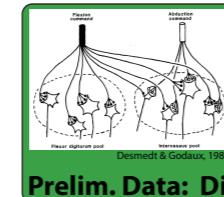
FDI SDN is parallel to overall force: noise is less of a problem



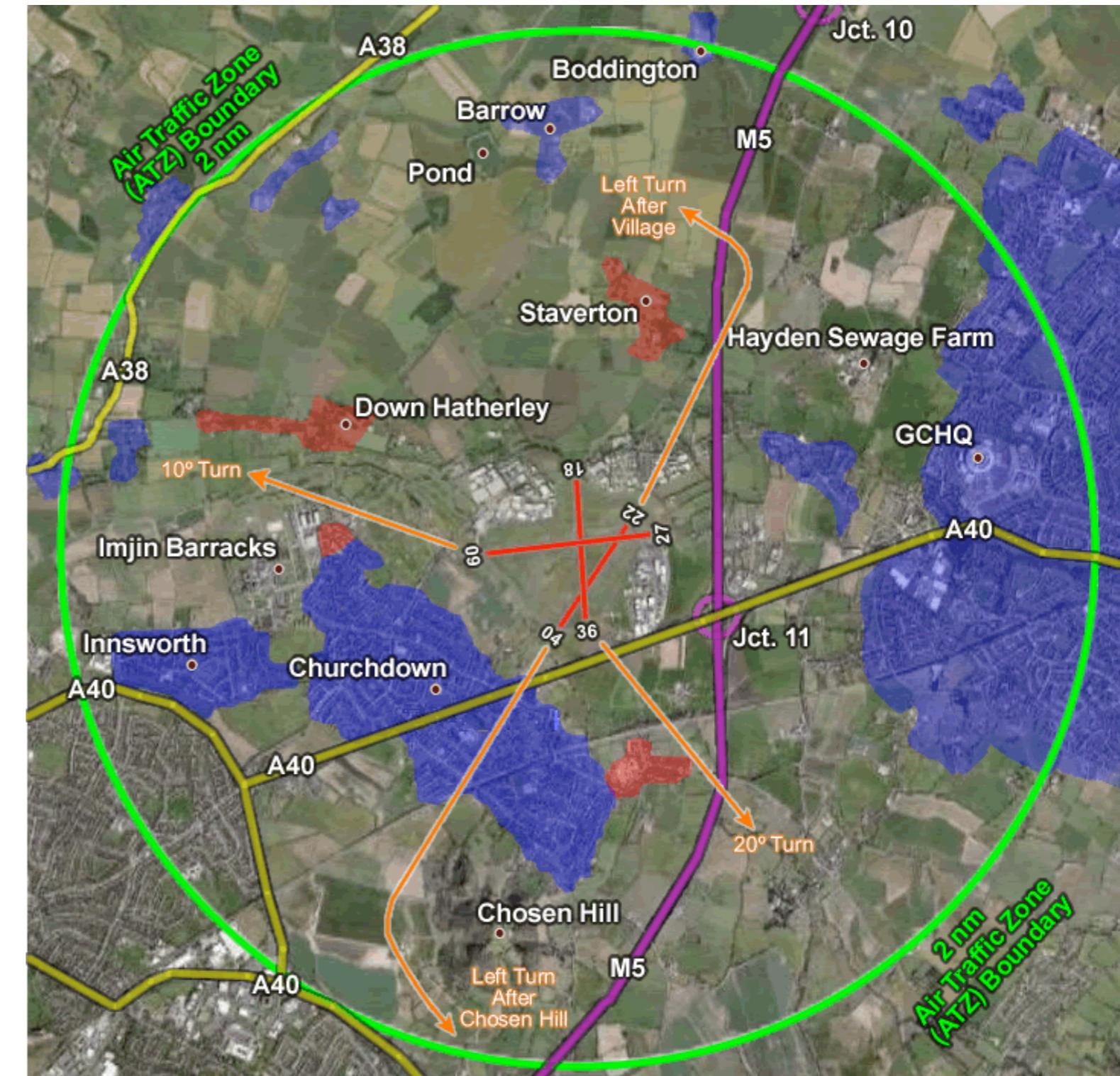
Background



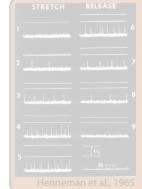
New Approach



Aviation noise abatement



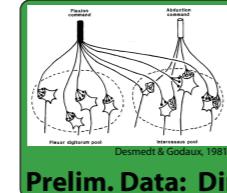
Gloucestershire Airport



Background



New Approach

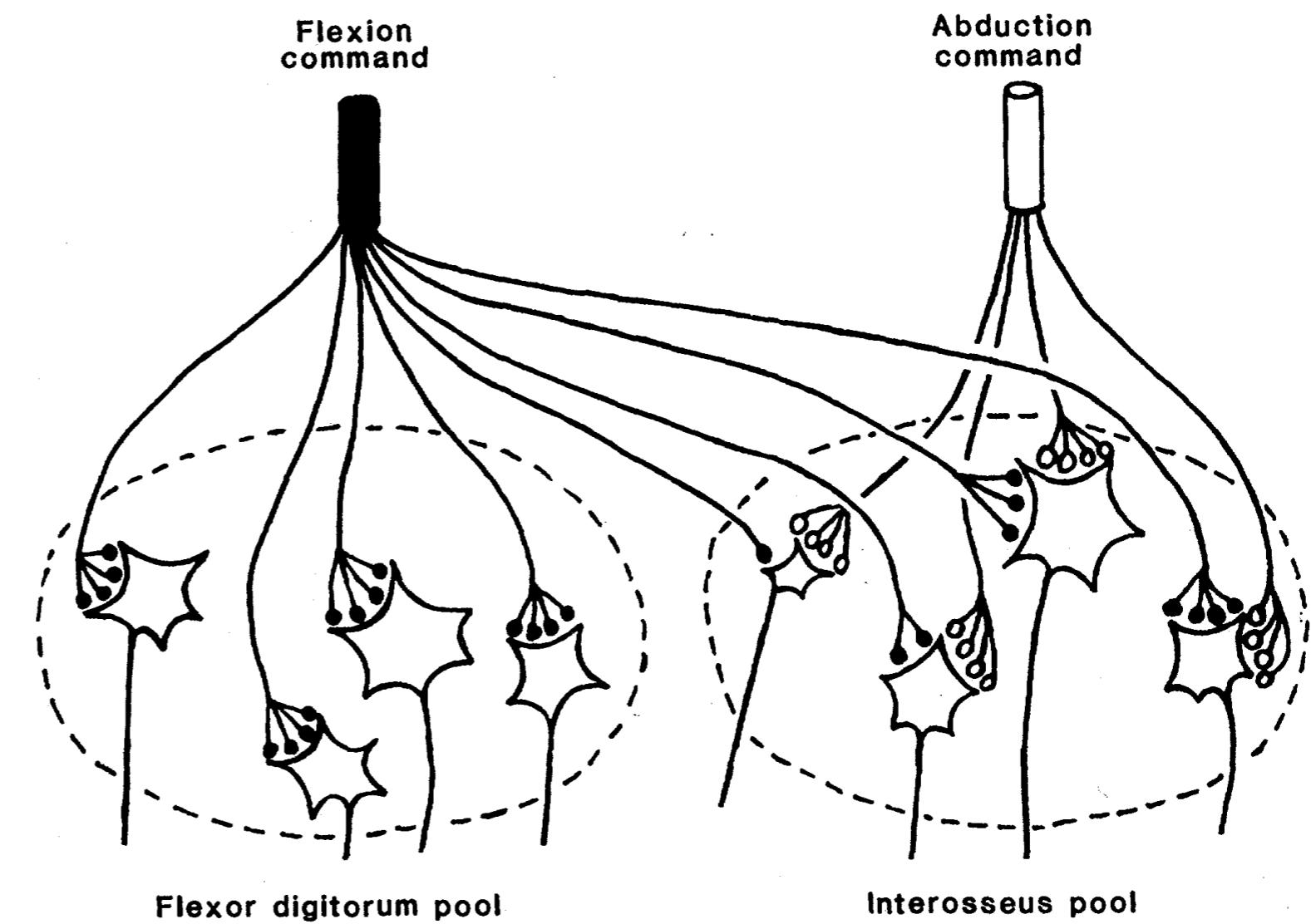


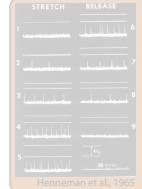
Prelim. Data: Direction



Prelim. Data: Stroke

Motor noise abatement?

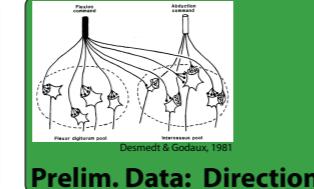




Background

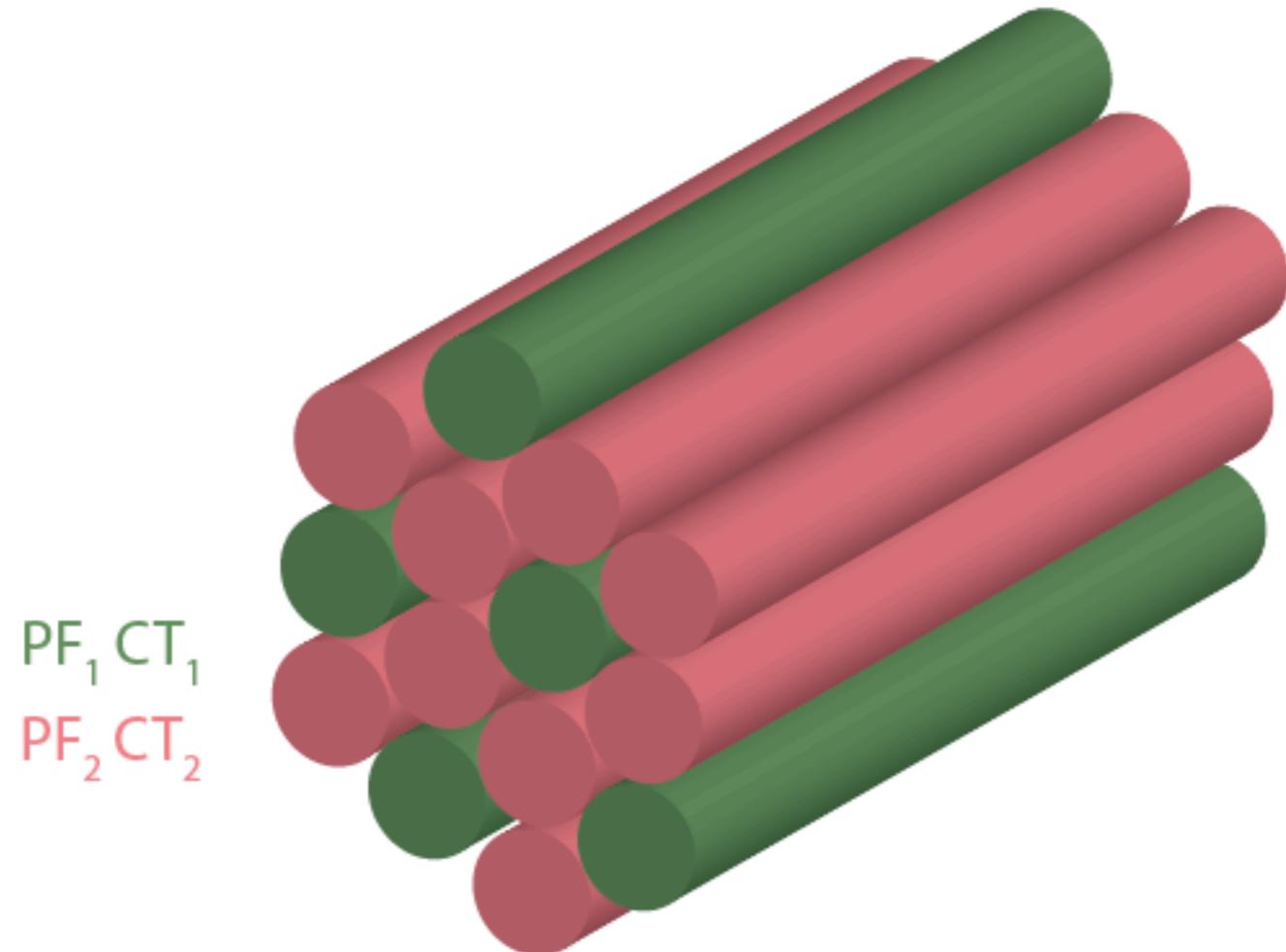


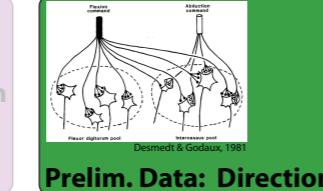
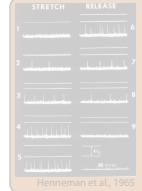
New Approach



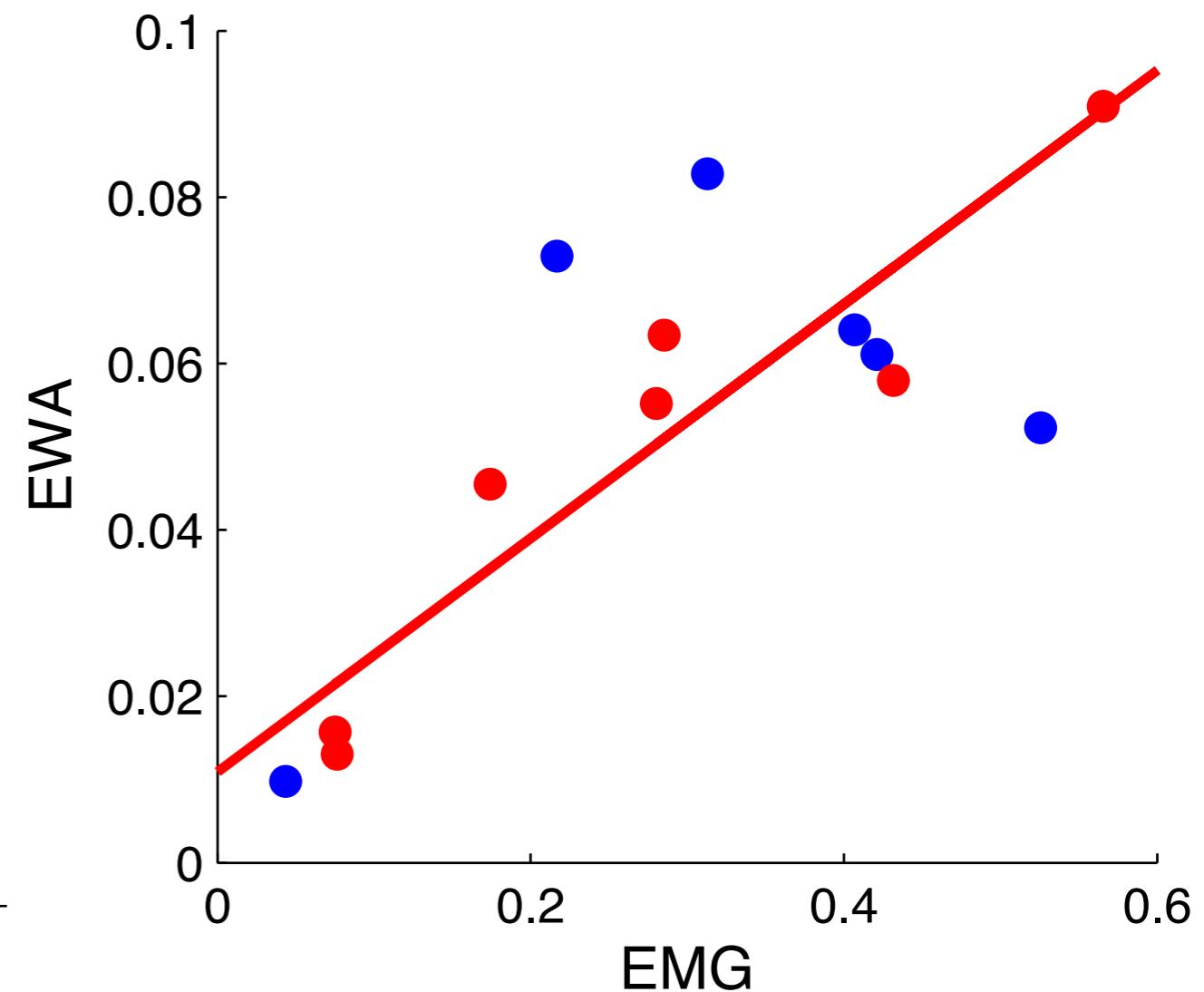
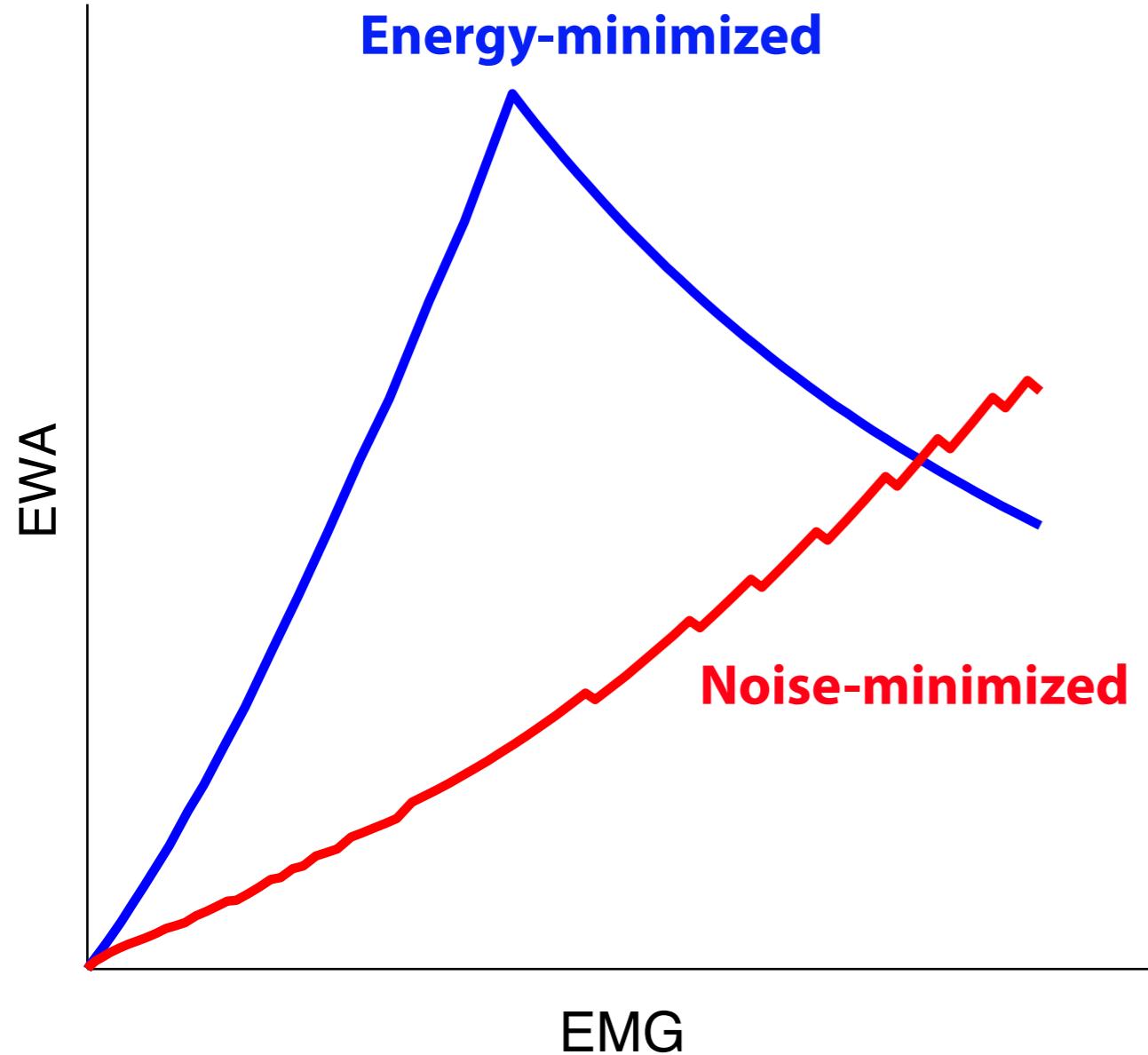
Noise abatement analysis

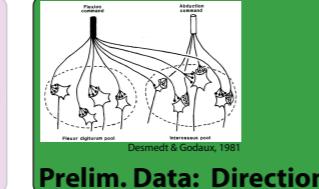
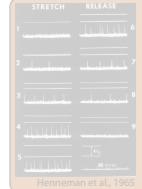
Can MU activation be altered to minimize noise?





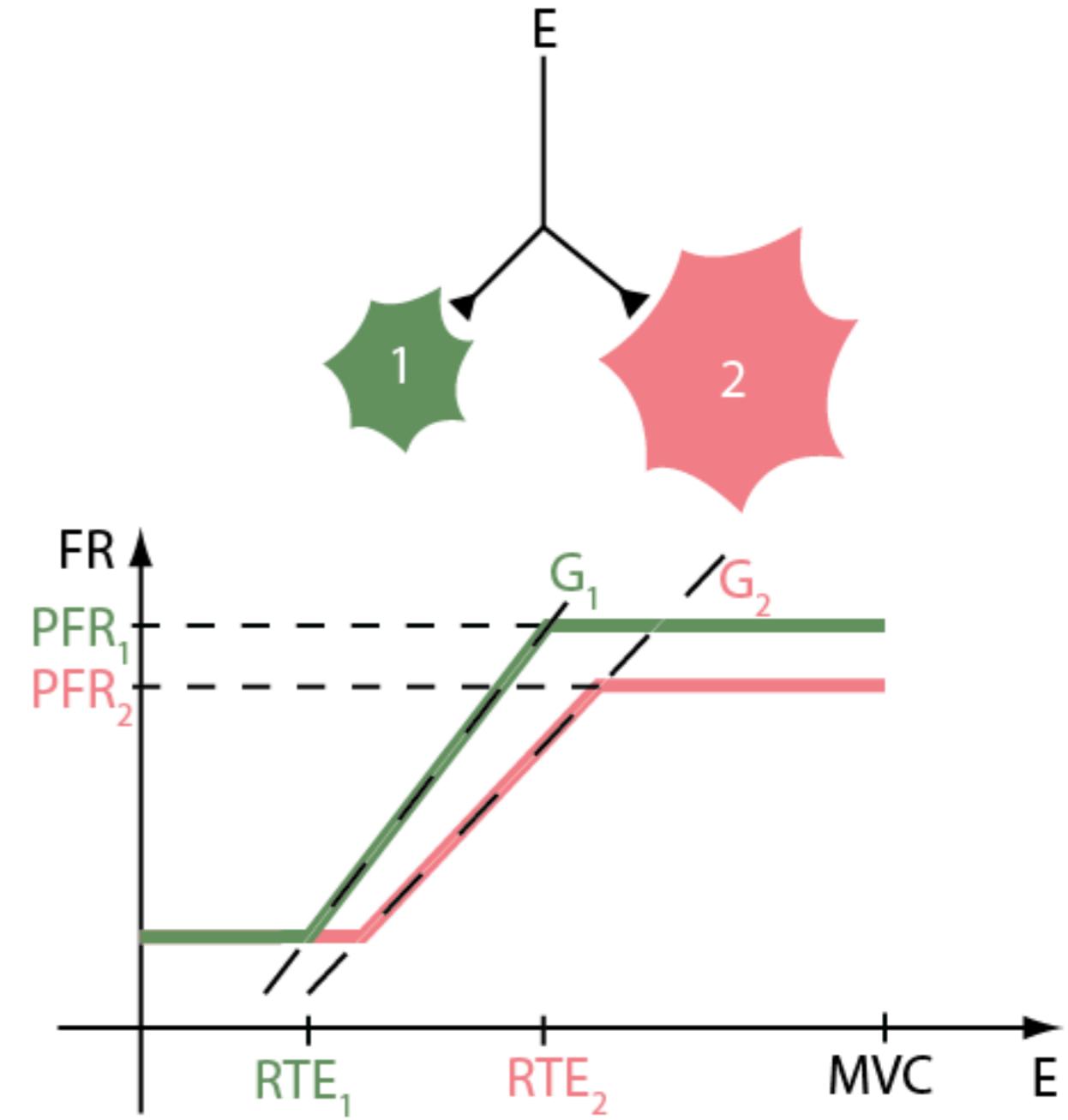
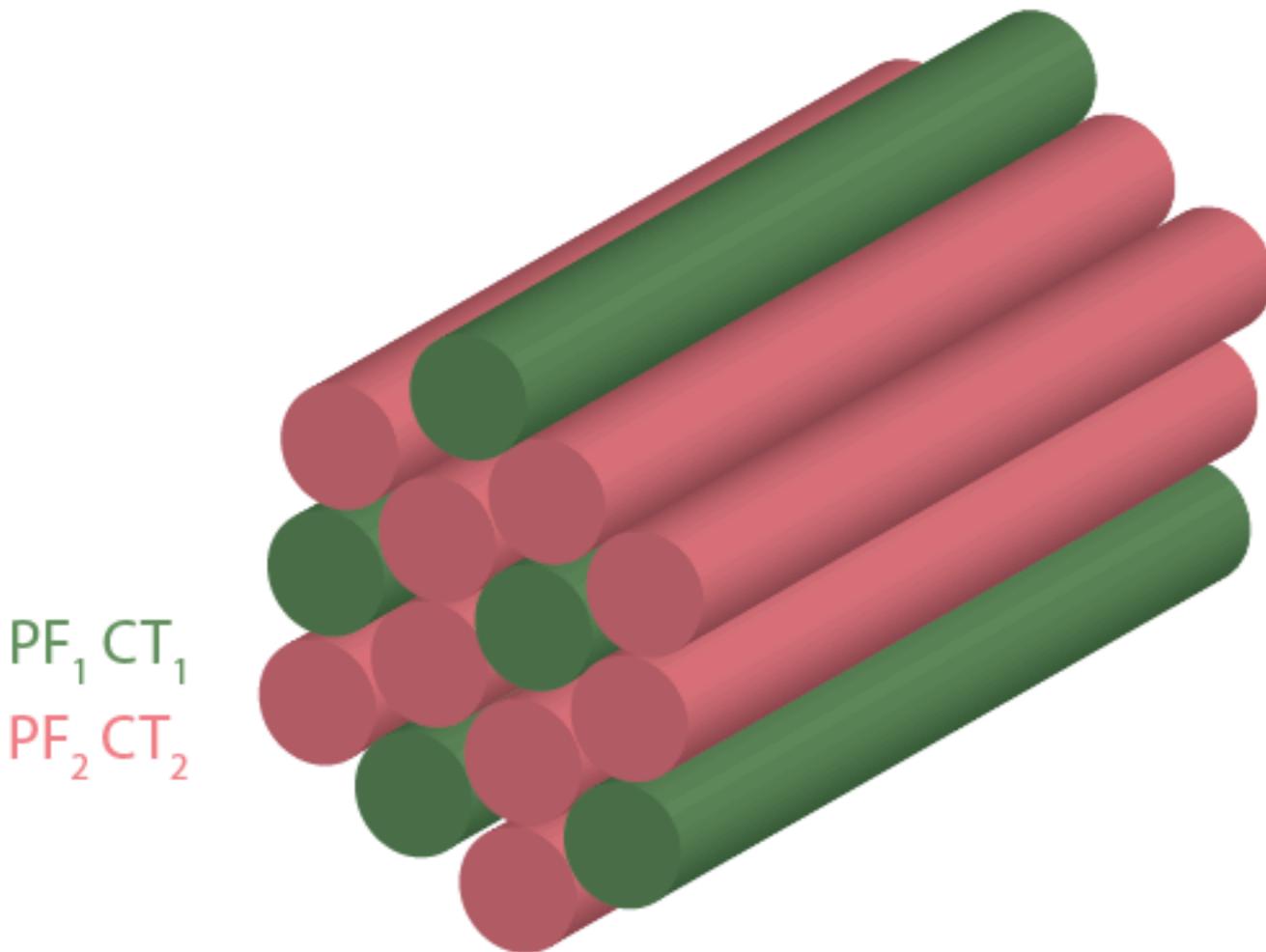
Minimizing noise

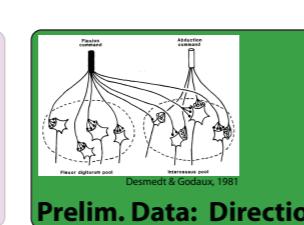




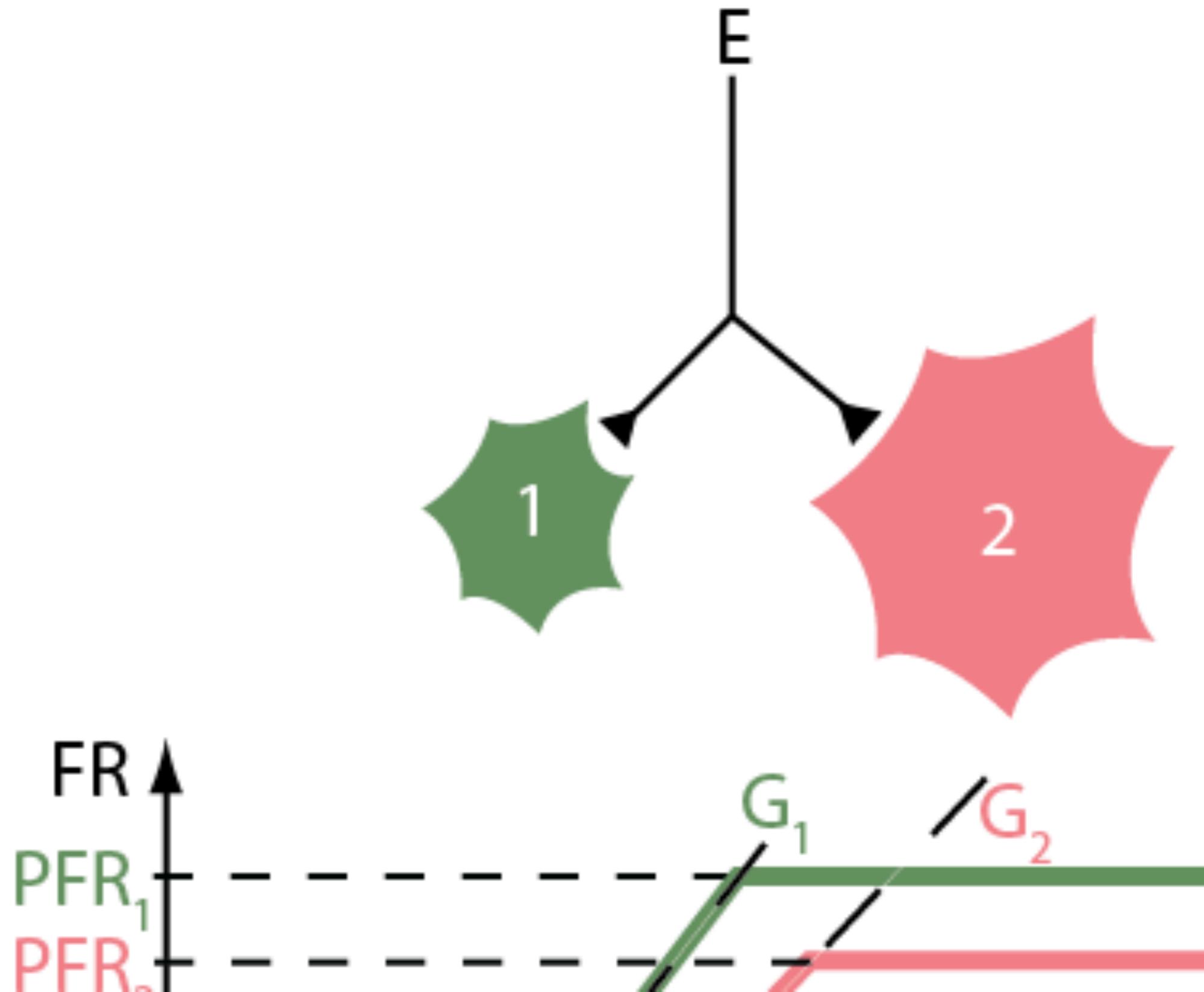
Noise abatement analysis

Can synaptic patterning be altered to minimize noise?





Noise abatement analysis



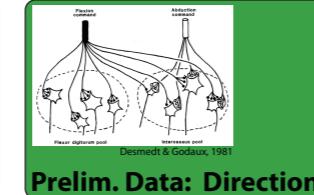
Noise abatement analysis



Background



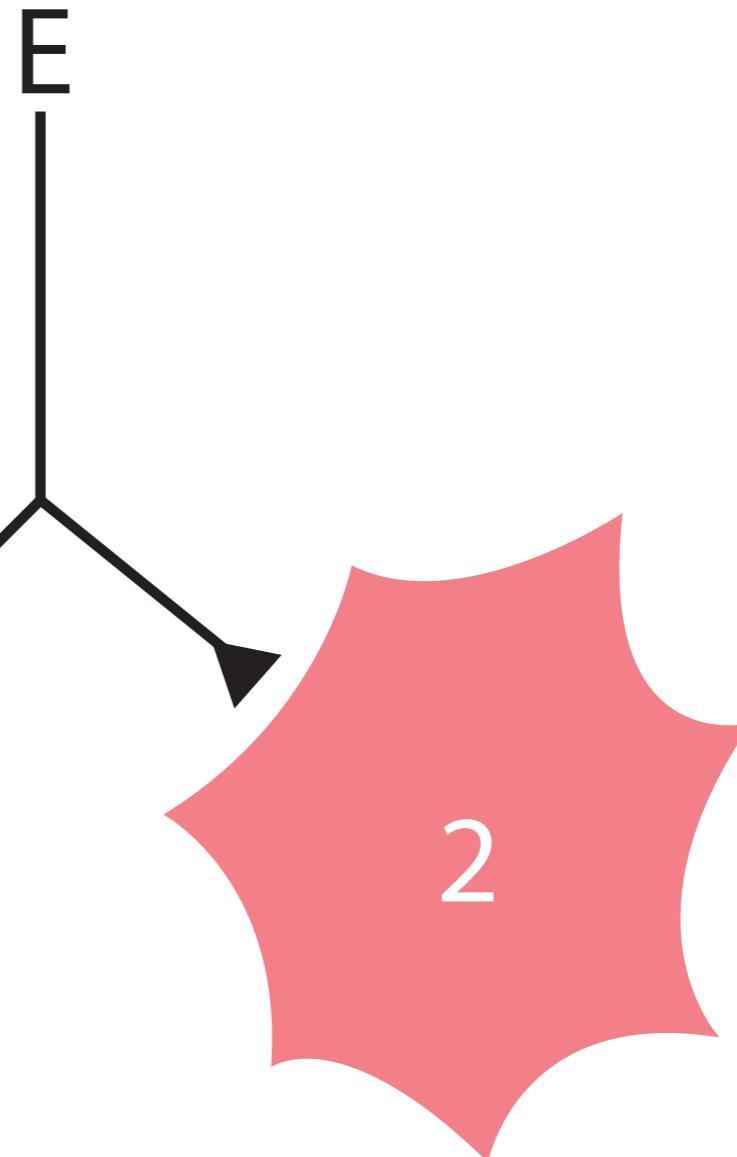
New Approach



1

S_1

2



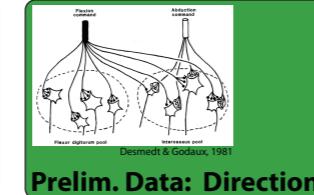
Noise abatement analysis



Background



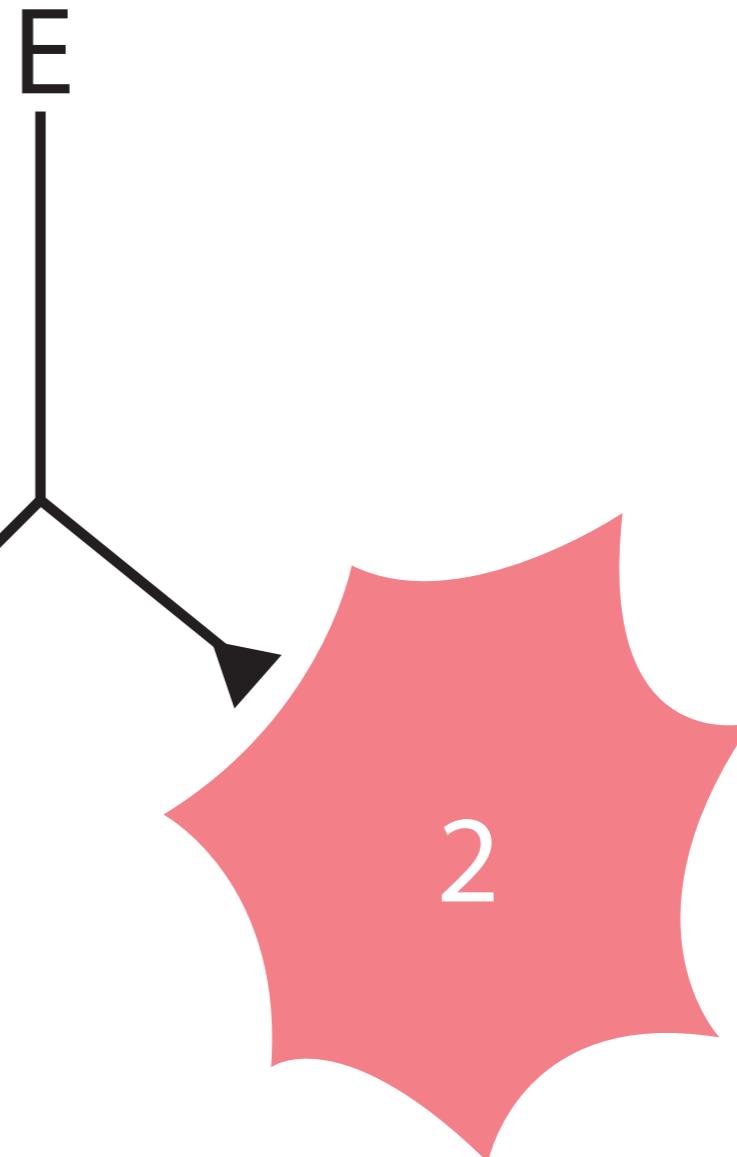
New Approach



1

S_1

2



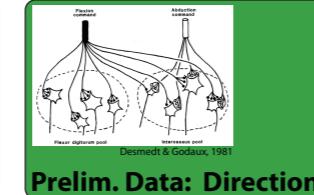
Noise abatement analysis



Background



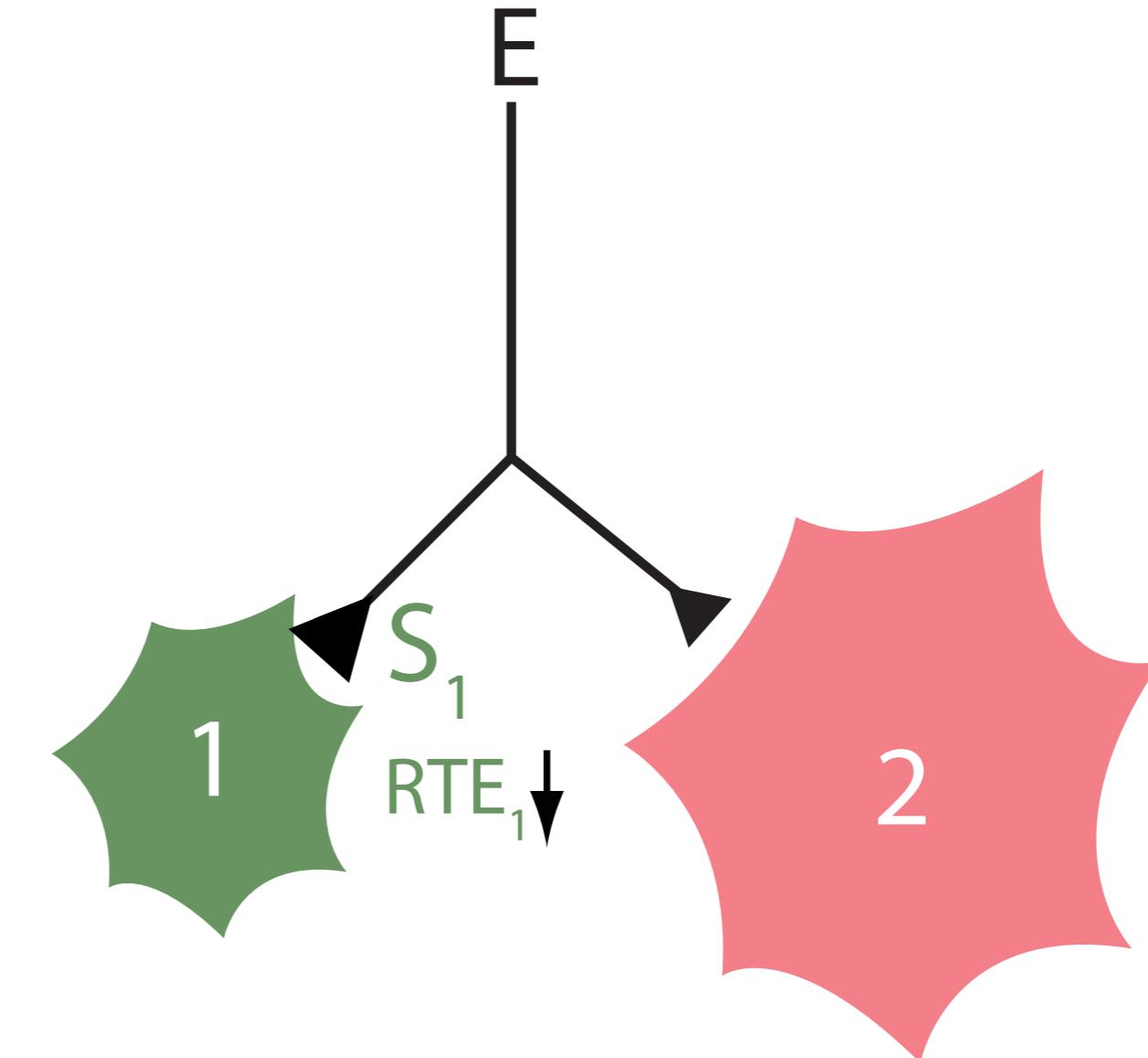
New Approach



Prelim. Data: Direction



Prelim. Data: Stroke



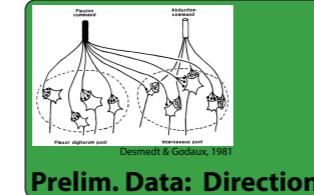
Noise abatement analysis



Background



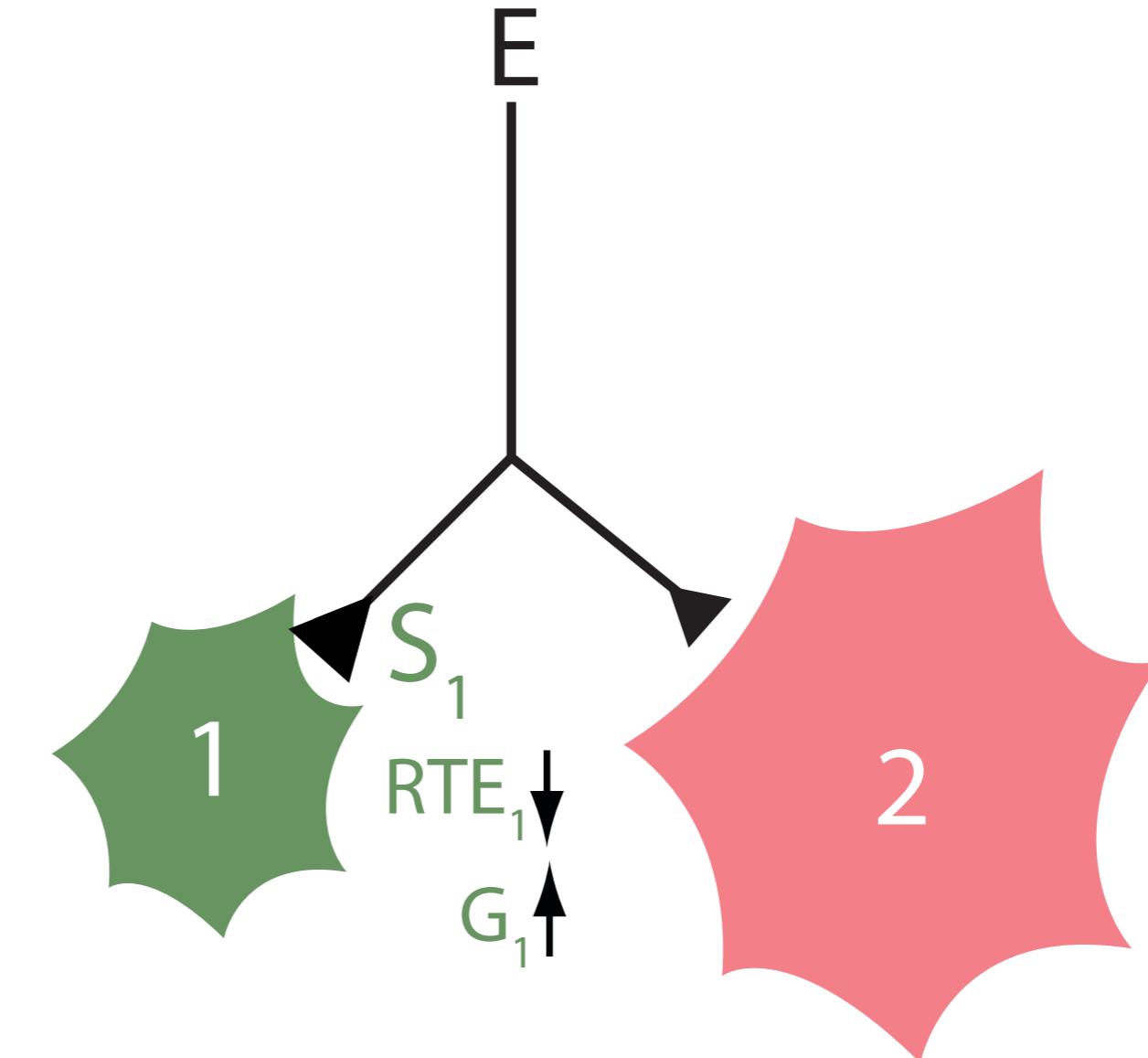
New Approach

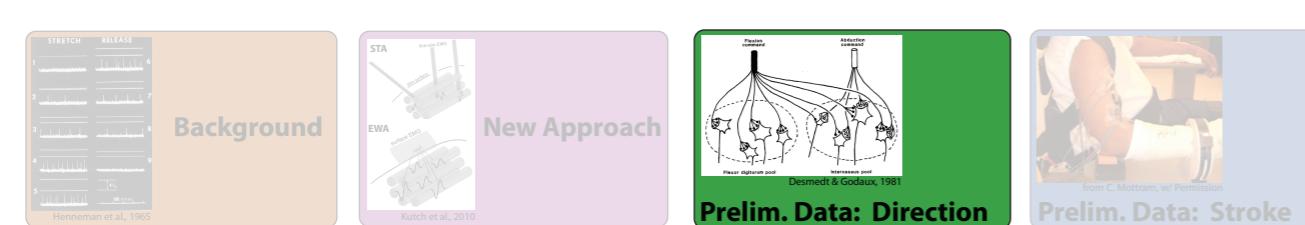


Prelim. Data: Direction

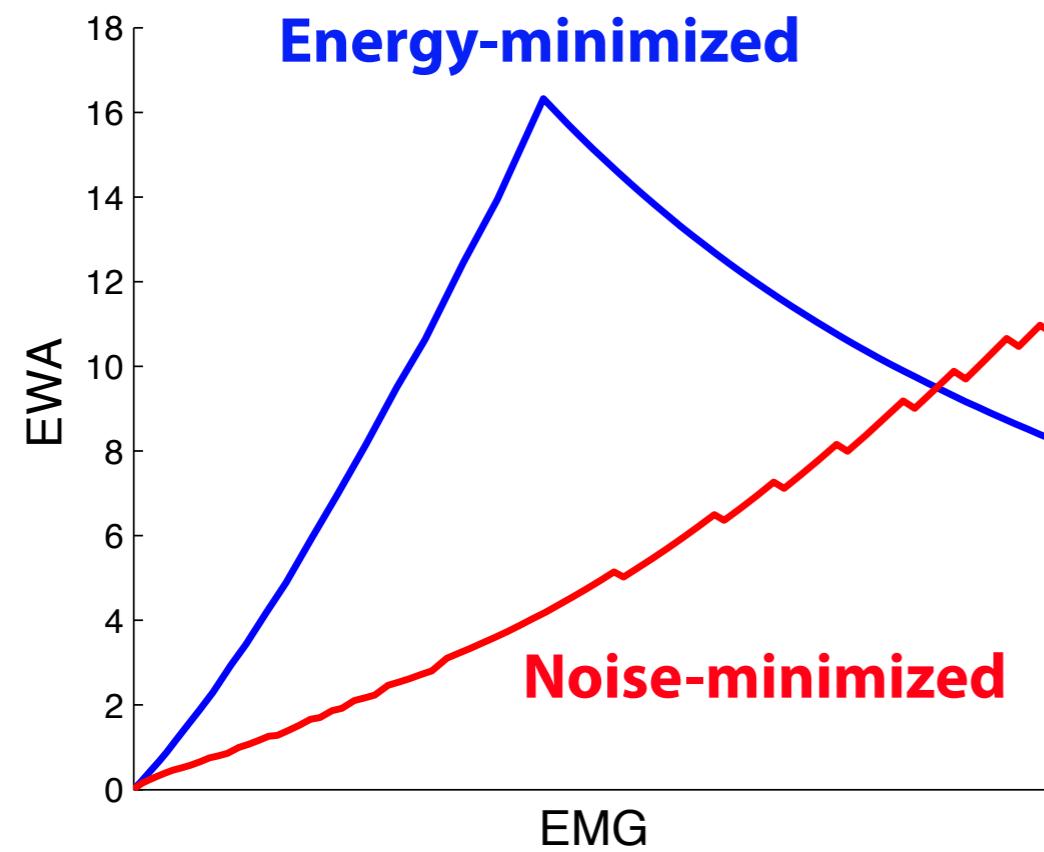
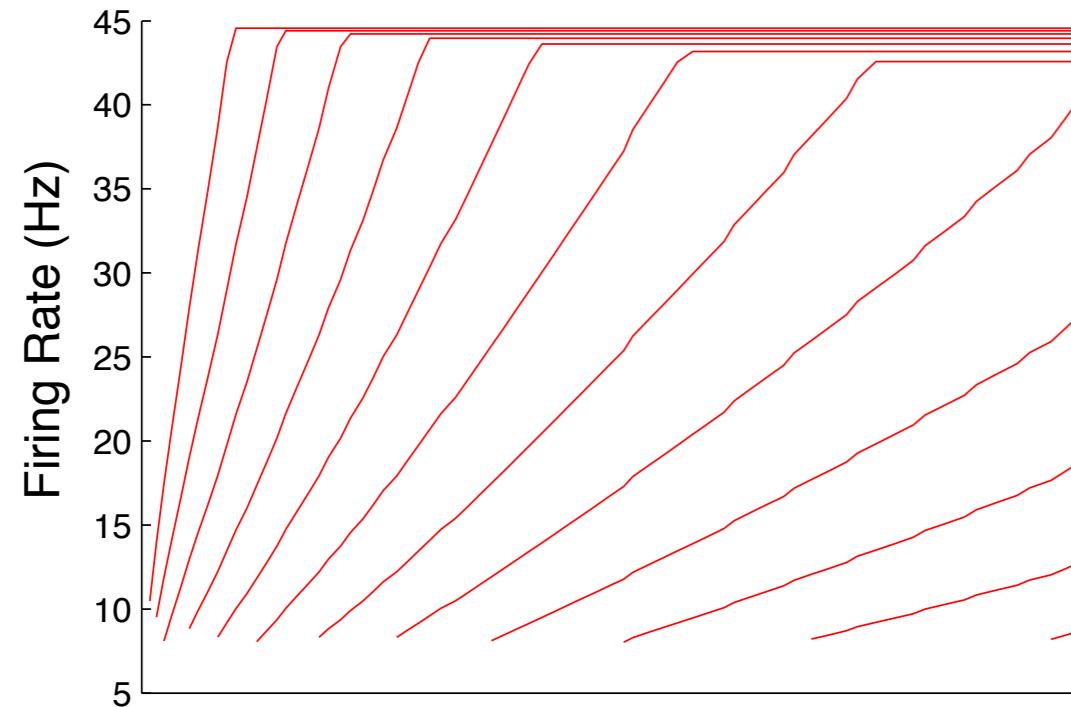


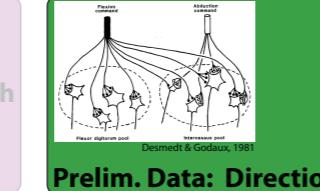
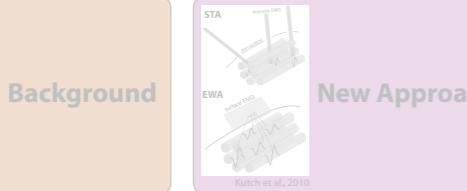
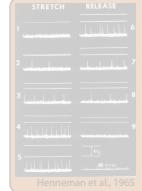
Prelim. Data: Stroke



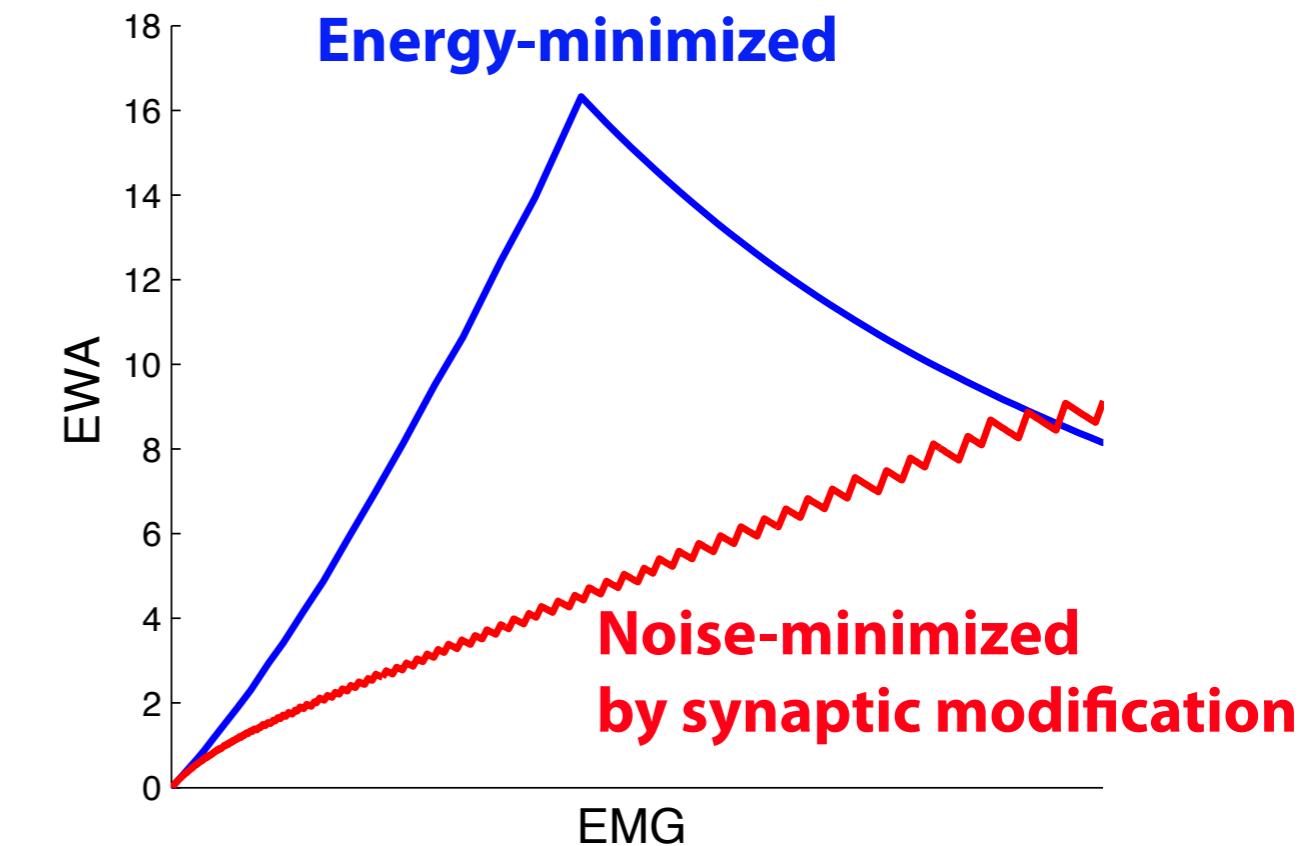
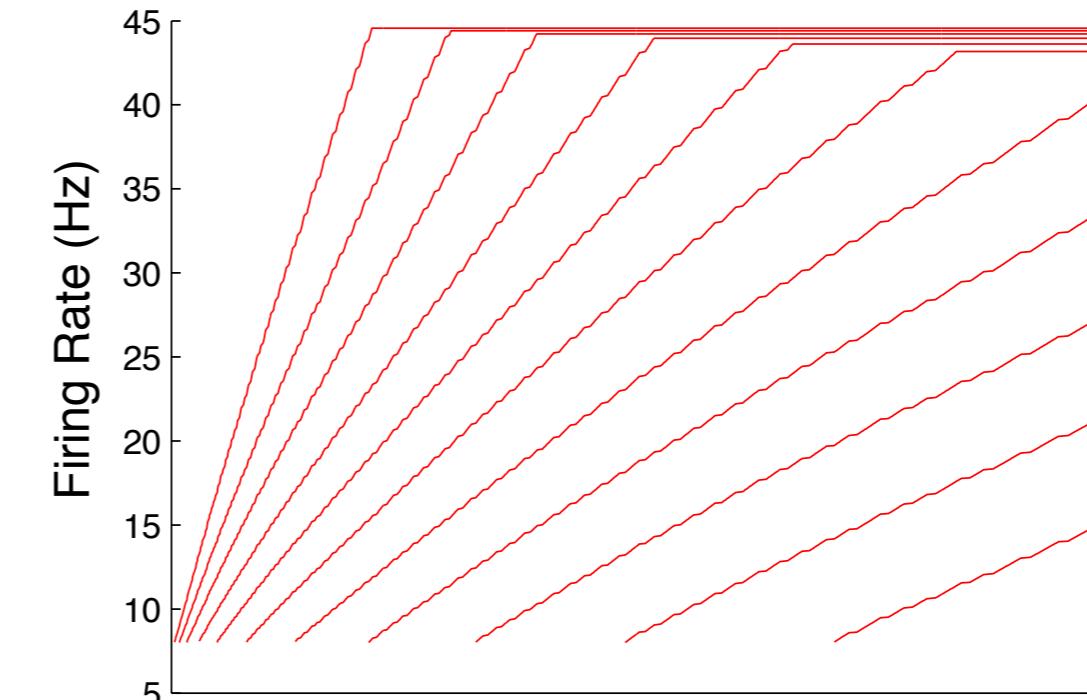
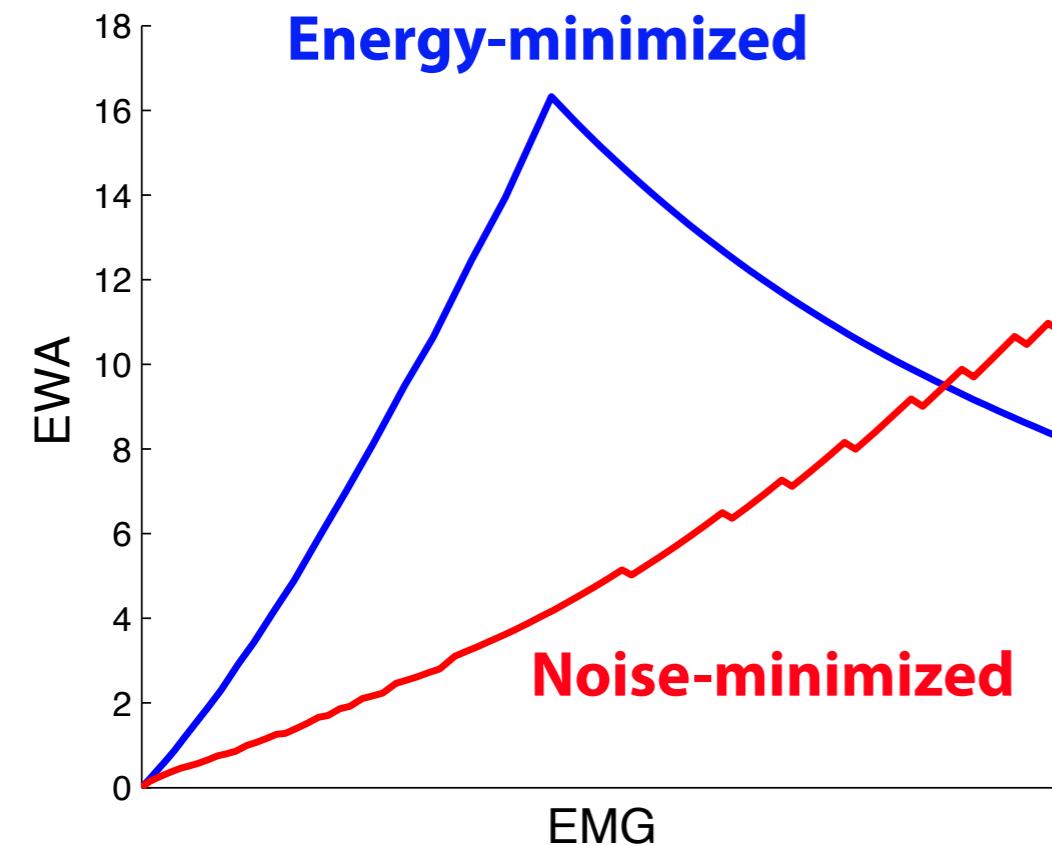
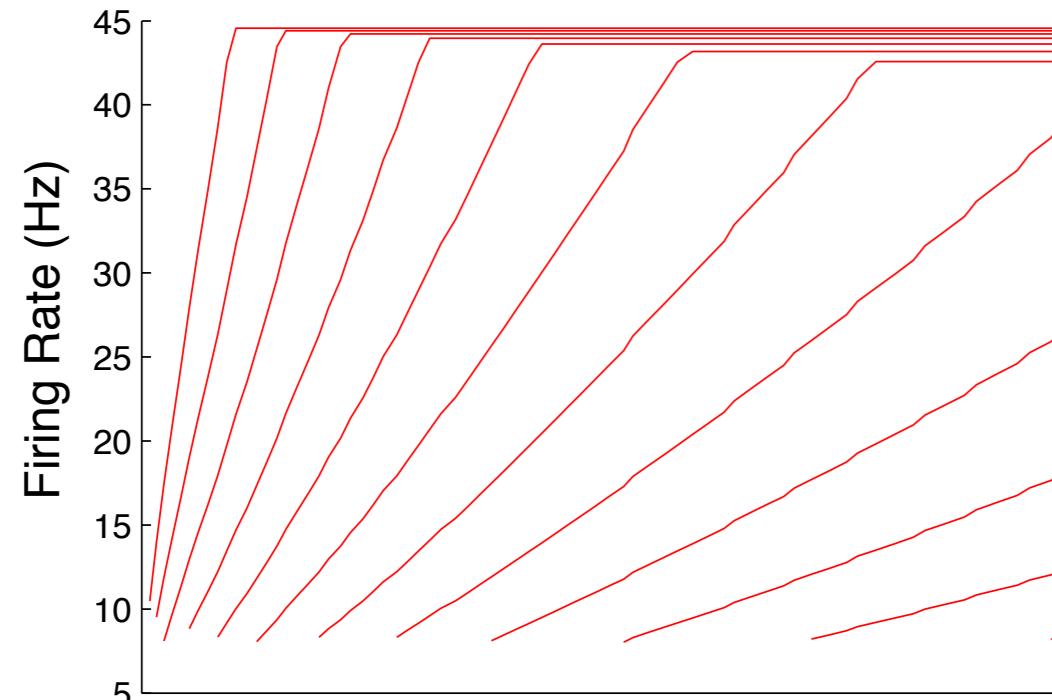


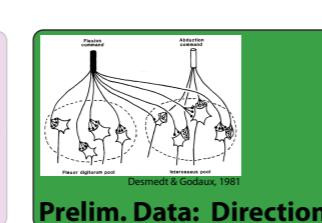
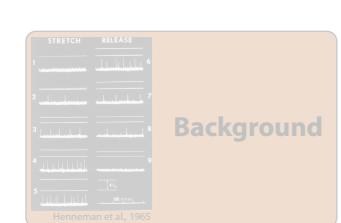
Neural noise-minimization



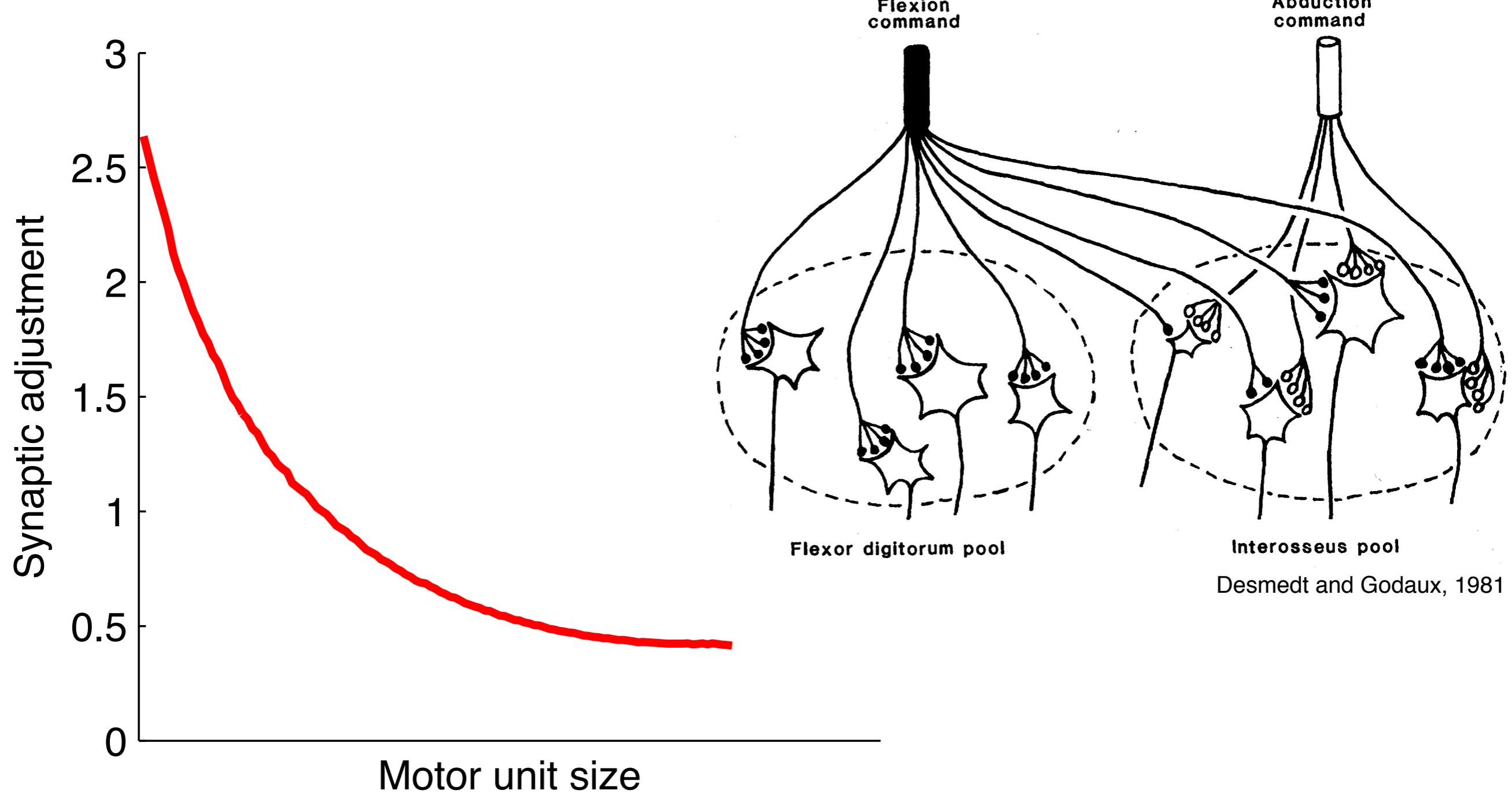


Neural noise-minimization





Hypothesis: non-uniform wiring is a scheme for noise abatement

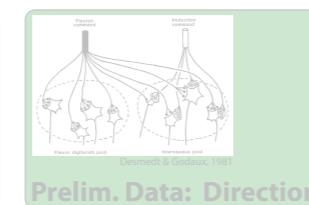




Background



New Approach

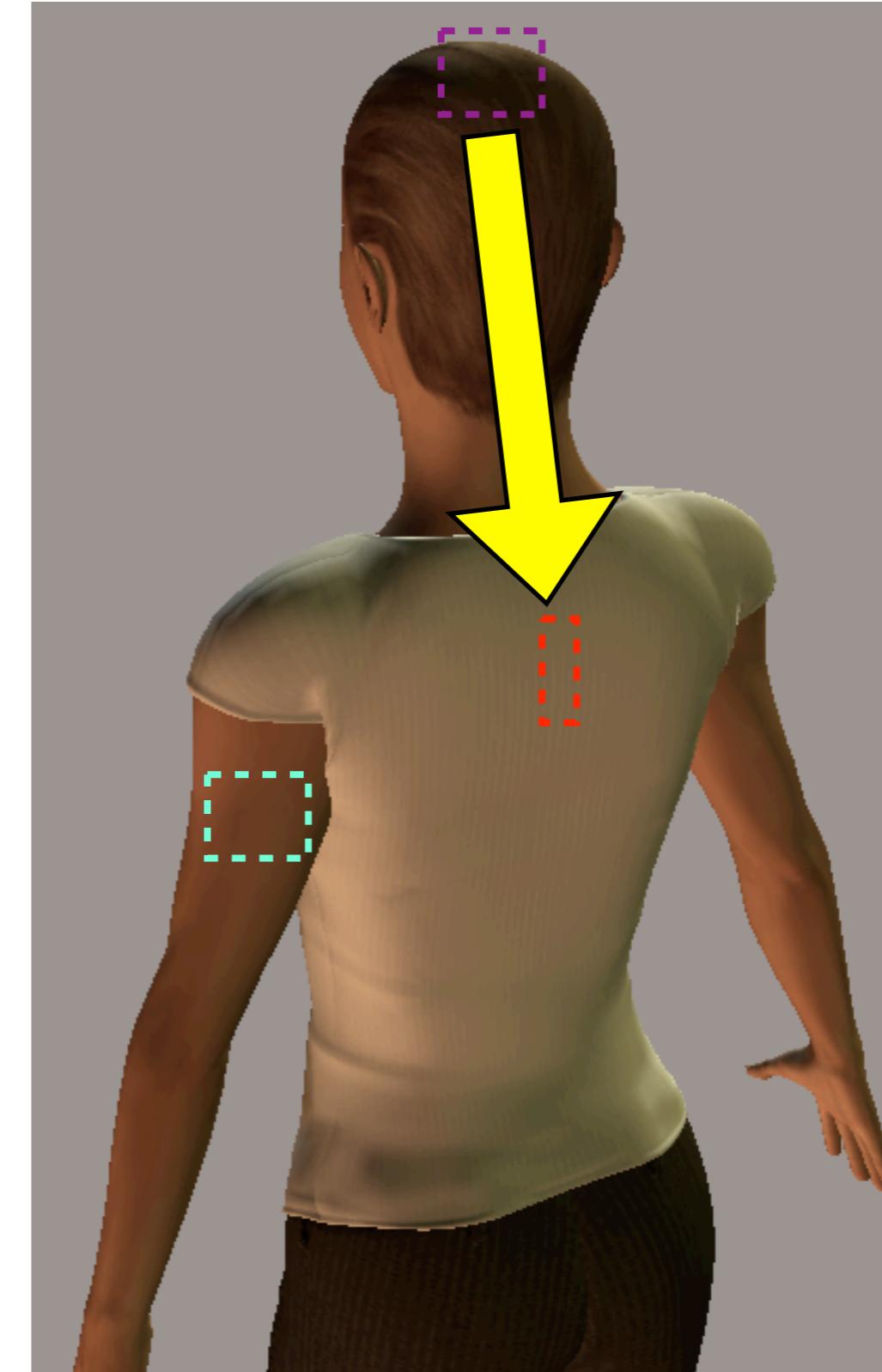


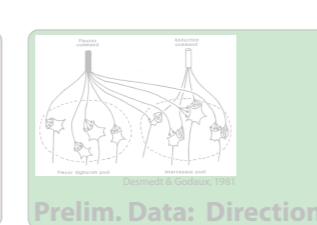
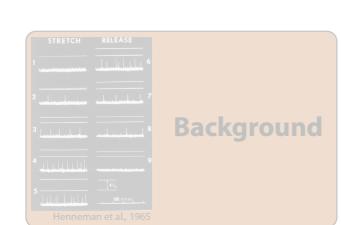
Prelim. Data: Direction



Prelim. Data: Stroke

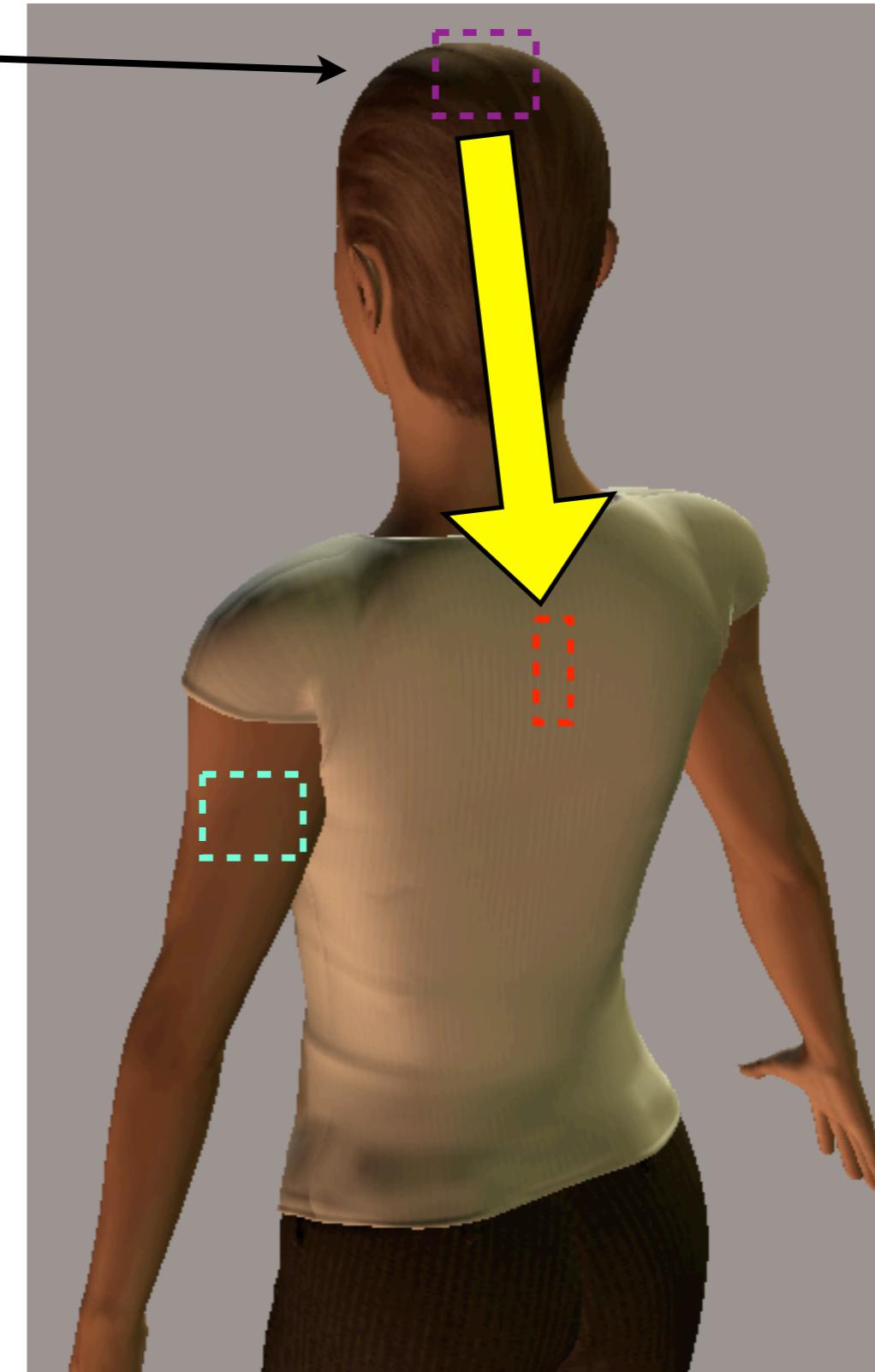
Where is post-stroke weakness and increased fatiguability from?

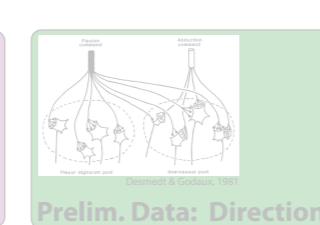
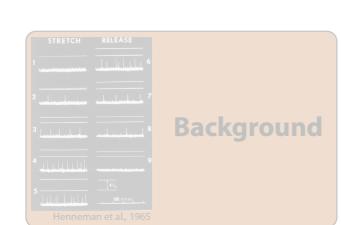




Where is post-stroke weakness and increased fatiguability from?

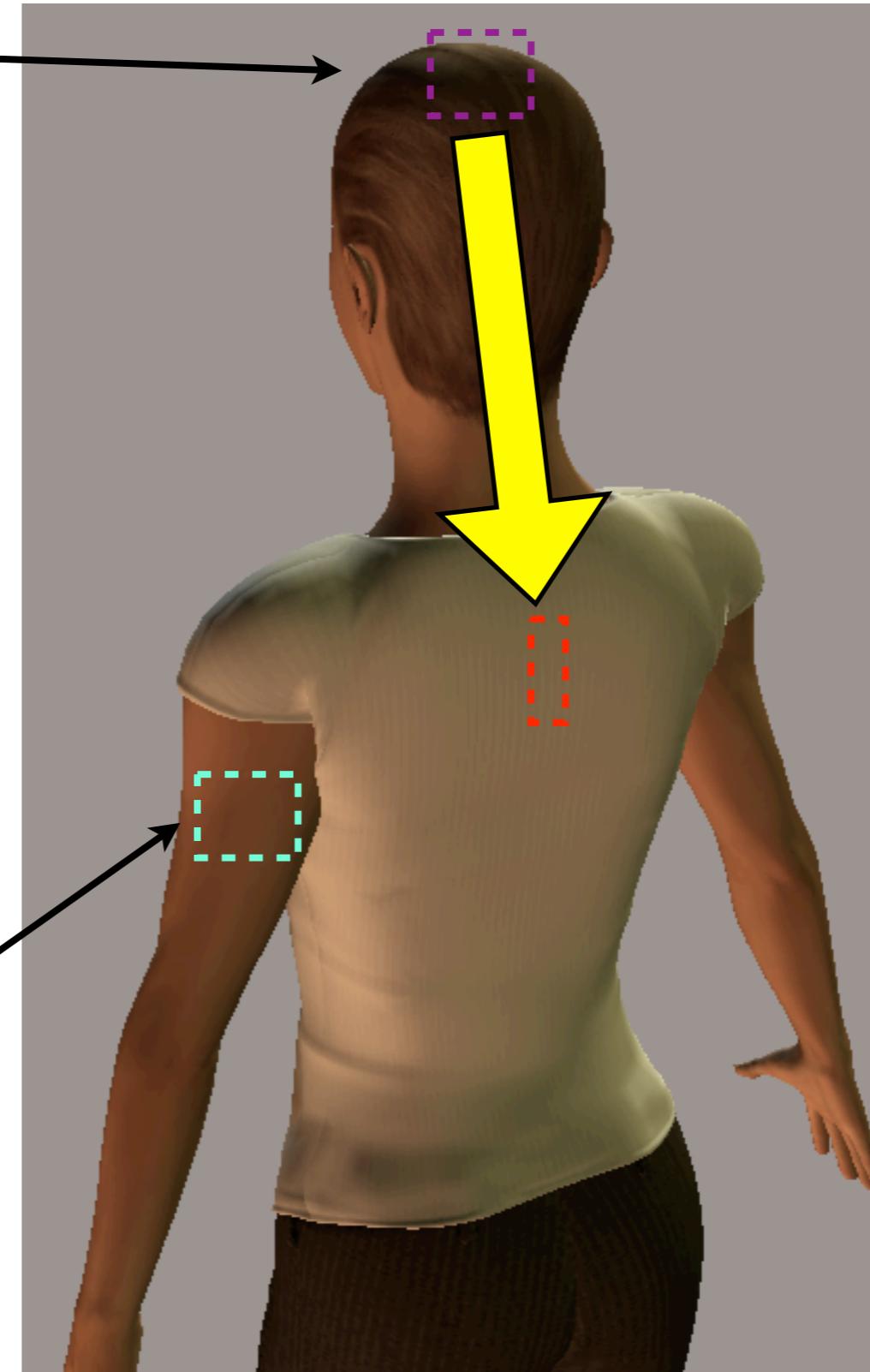
Hughlings Jackson, 19th century



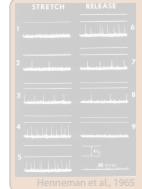


Where is post-stroke weakness and increased fatiguability from?

Hughlings Jackson, 19th century



Hafer-Macko et al. 2008



Background



New Approach



Prelim. Data: Direction



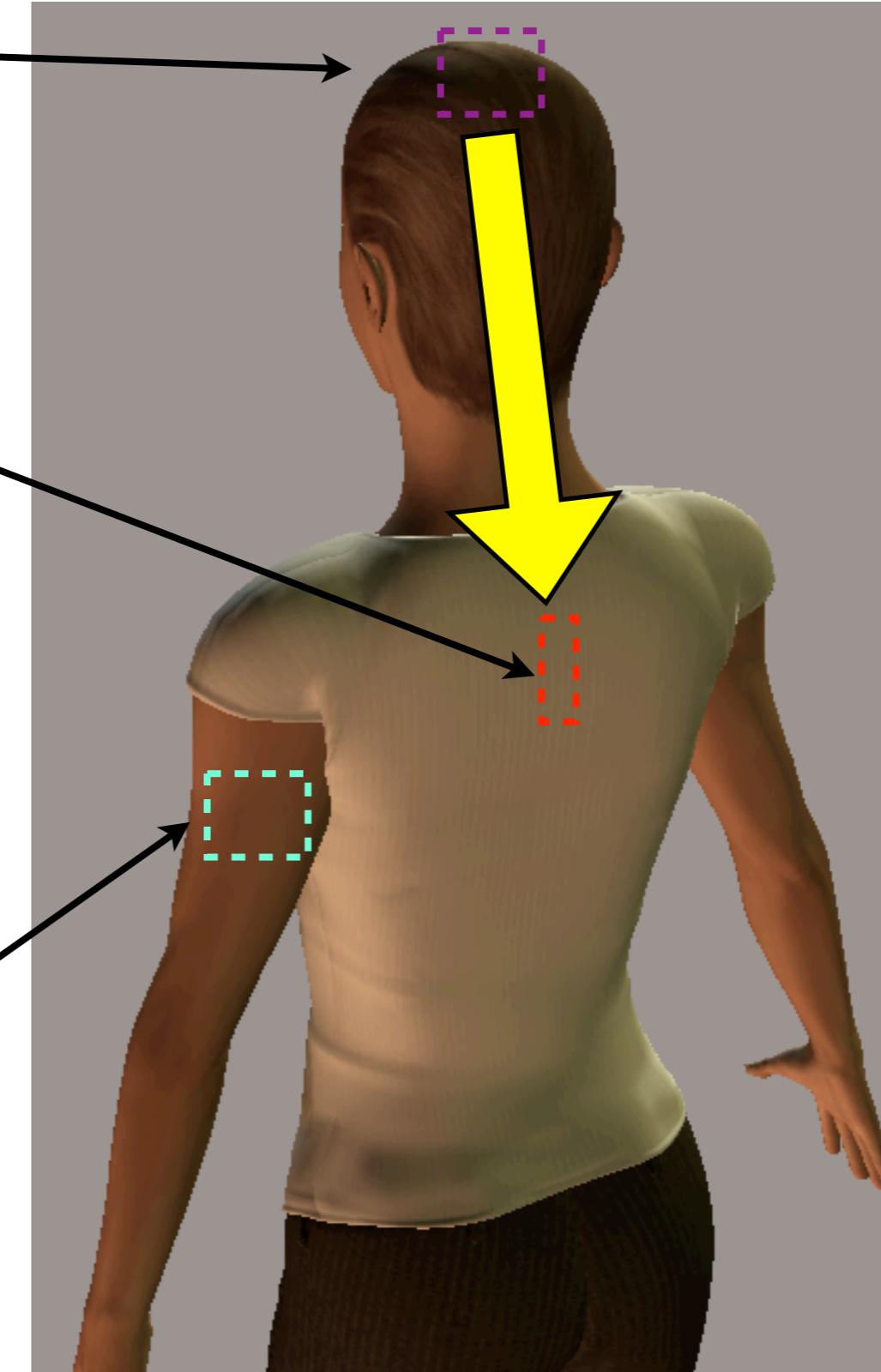
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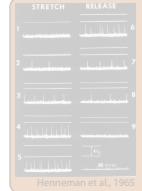
Where is post-stroke weakness and increased fatiguability from?

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Gemperline et al. 1995

Hafer-Macko et al. 2008

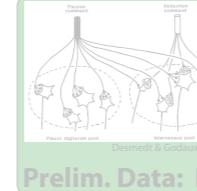




Background



New Approach



Prelim. Data: Direction

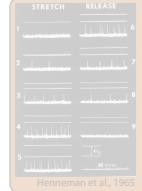


Prelim. Data: Stroke

Collaboration

Megan Conrad @ RIC





Background



New Approach

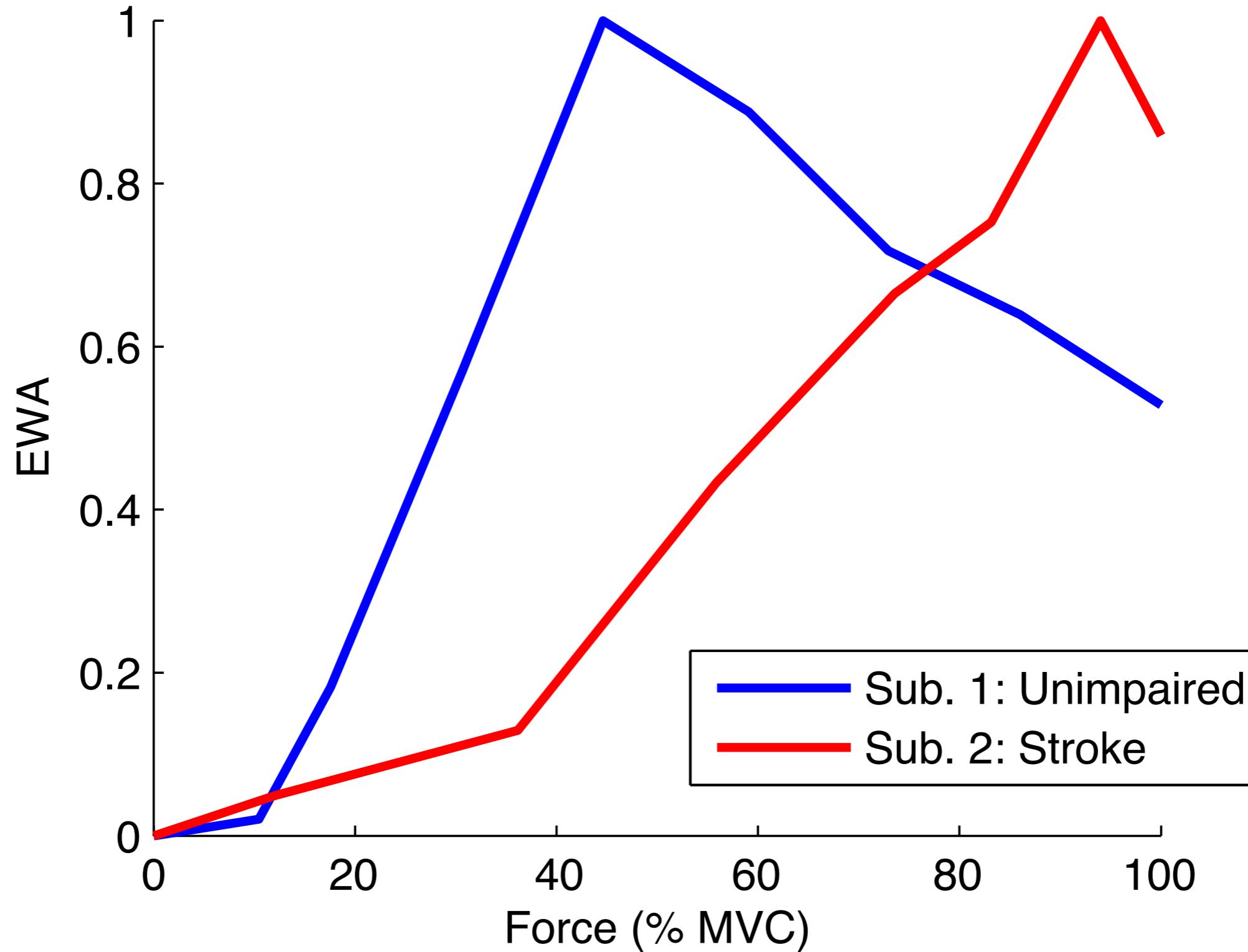


Prelim. Data: Direction

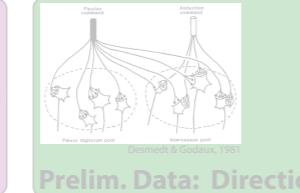
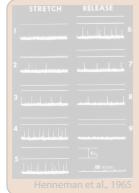


Prelim. Data: Stroke

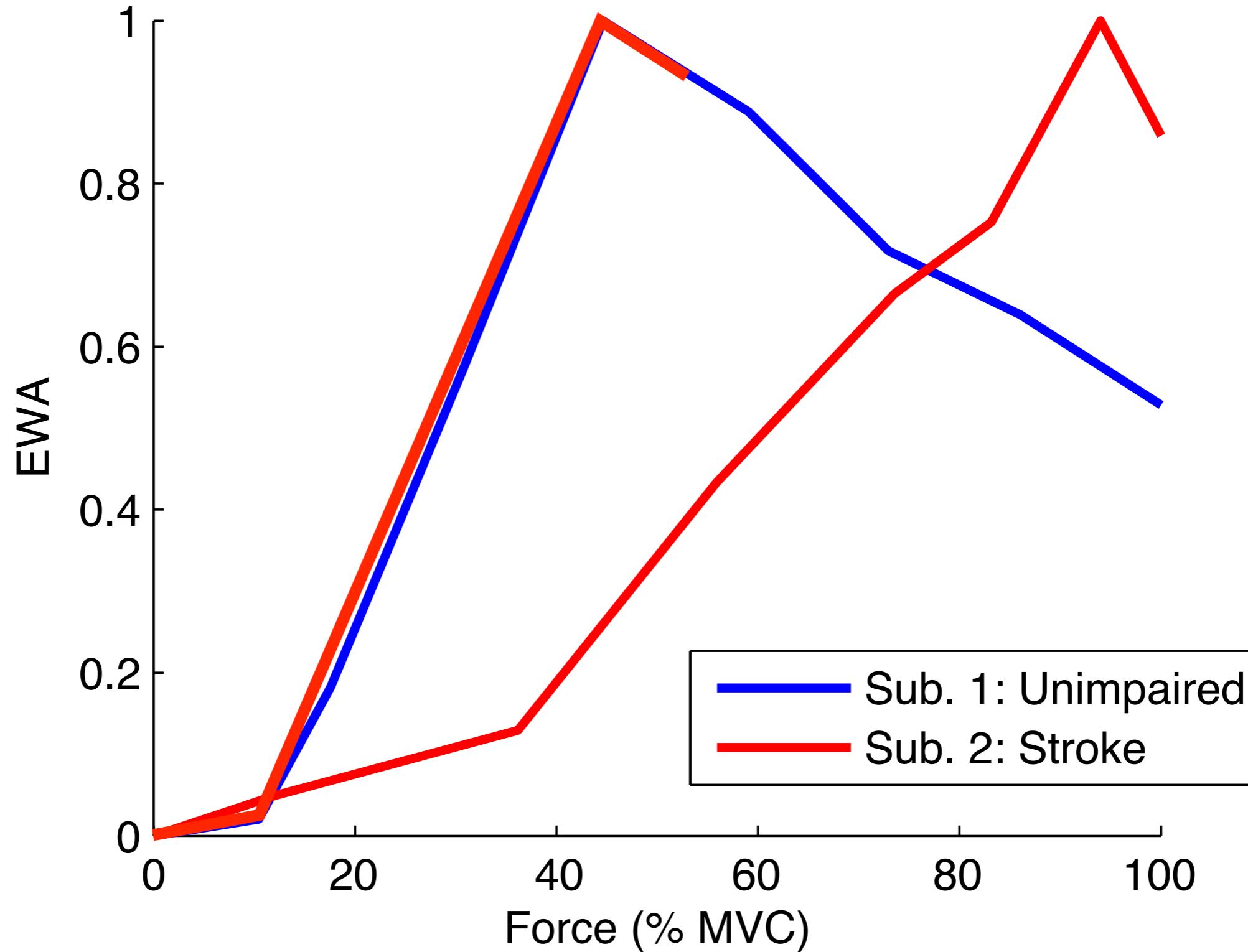
EWA shift post-stroke



* 48 year old male, Chedoke Hand Stage 5 (Moderate Impairment), 1 year post-stroke



EWA shift post-stroke



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Conclusions

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Conclusions

1. **EMG-weighted averaging (EWA):** non-invasive tool for characterizing bulk motor unit properties and activation pattern.
2. MU activation pattern changes during synergistic activation may be a mechanism for noise abatement.
3. Noninvasive motor unit characterization, including EWA, has the potential for large scale study of long-standing scientific and clinical questions.

Acknowledgements



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CJ Heckman



Francisco
Valero-Cuevas



Manish Kurse



Tony Bloch



Nina Suresh



Zev Rymer



Heiko Hoffman



Josh Inouye

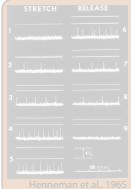
Megan Conrad

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1. NIH: PI of NINDS NRSA Training Grant 1F31NS057855-01 (JJK and WZR)
2. NIH: AR-050520 and AR-052345 (FVC)
3. NSF: EFRI-COPN 0836042 (FVC) and DMS-0604307 and CMS-0408542 (AMB)



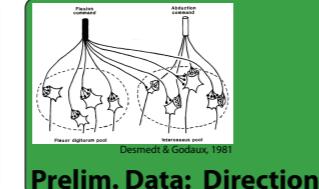
Thank you



Background



New Approach



Prelim. Data: Direction



Prelim. Data: Stroke

Why would motor unit activation change with direction?



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Muscle redundancy does not imply robustness to muscle dysfunction

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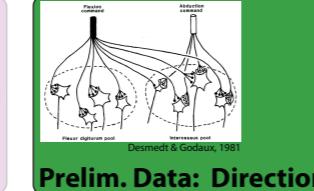
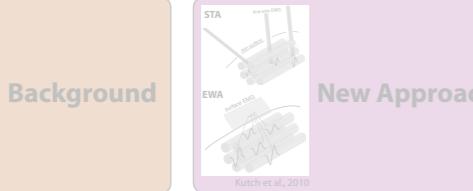
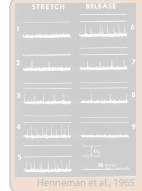
Computational models

Limb biomechanics

ABSTRACT

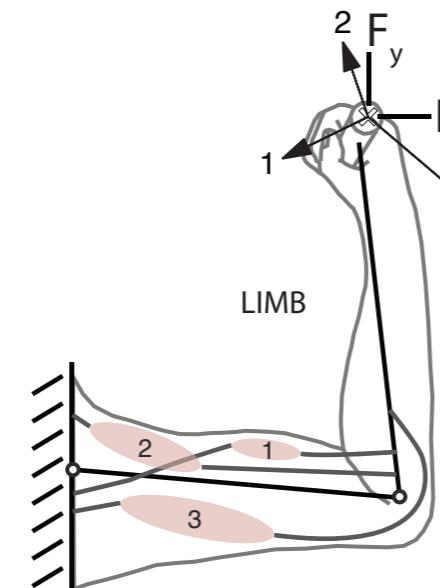
It is well-known that muscle redundancy grants the CNS numerous options to perform a task. Does muscle redundancy, however, allow sufficient robustness to compensate for loss or dysfunction of even a single muscle? Are all muscles equally redundant? We combined experimental and computational approaches to establish the limits of motor robustness for static force production. In computer-controlled cadaveric index fingers, we find that only a small subset (<5%) of feasible forces is robust to loss of any one muscle. Importantly, the loss of certain muscles compromises force production significantly more than others. Further computational modeling of a multi-joint, multi-muscle leg demonstrates that this severe lack of robustness generalizes to whole limbs. These results provide a biomechanical basis to begin to explain why redundant motor systems can be vulnerable to even mild neuromuscular pathology.

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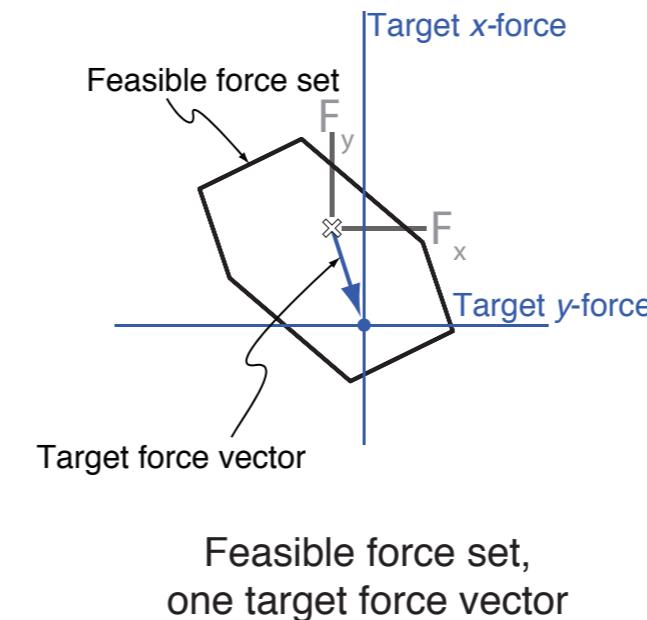


Task-specific activation ranges

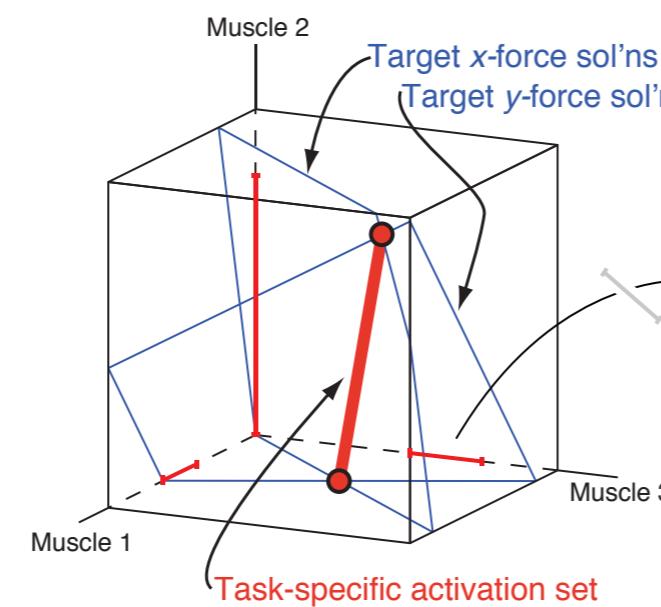
a



b

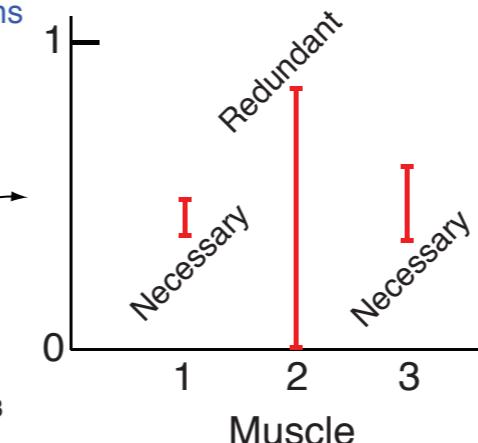


c

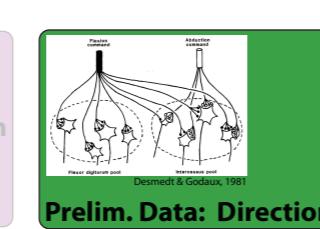


Solutions in muscle activation space, task-specific activation set

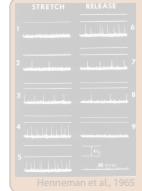
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Task-specific activation ranges



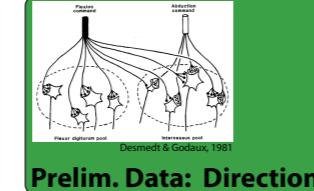
FDI must be active for flexion pinch



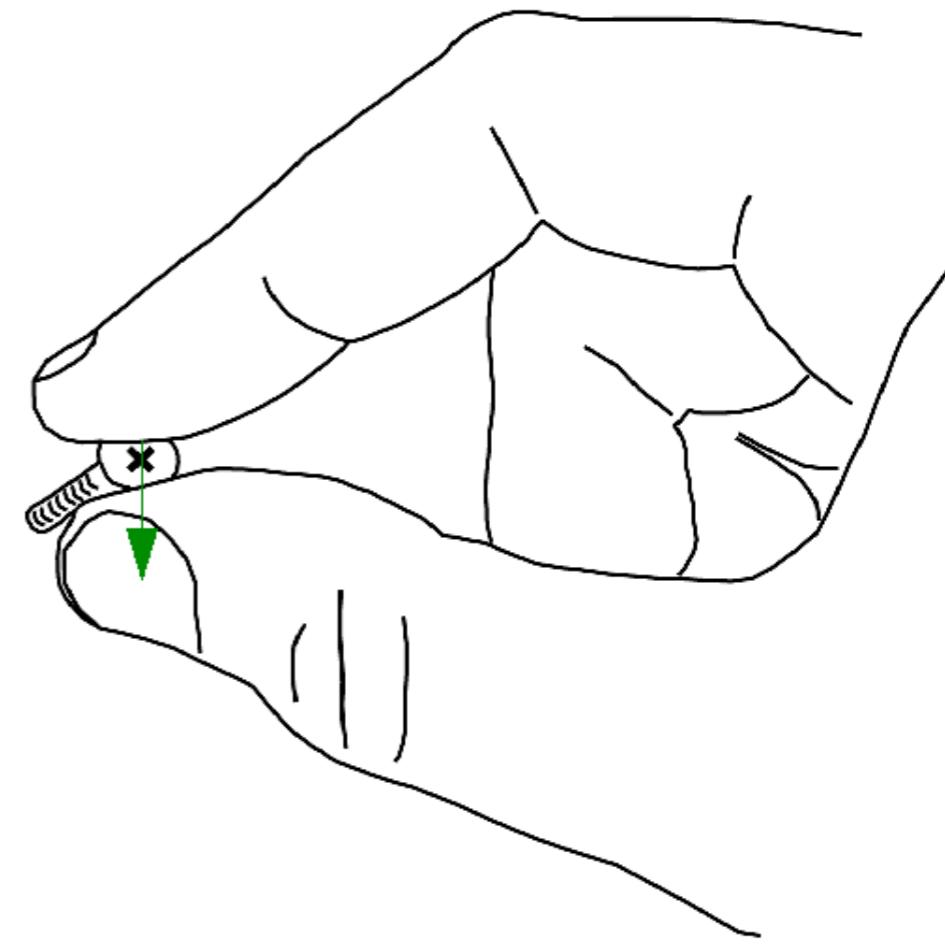
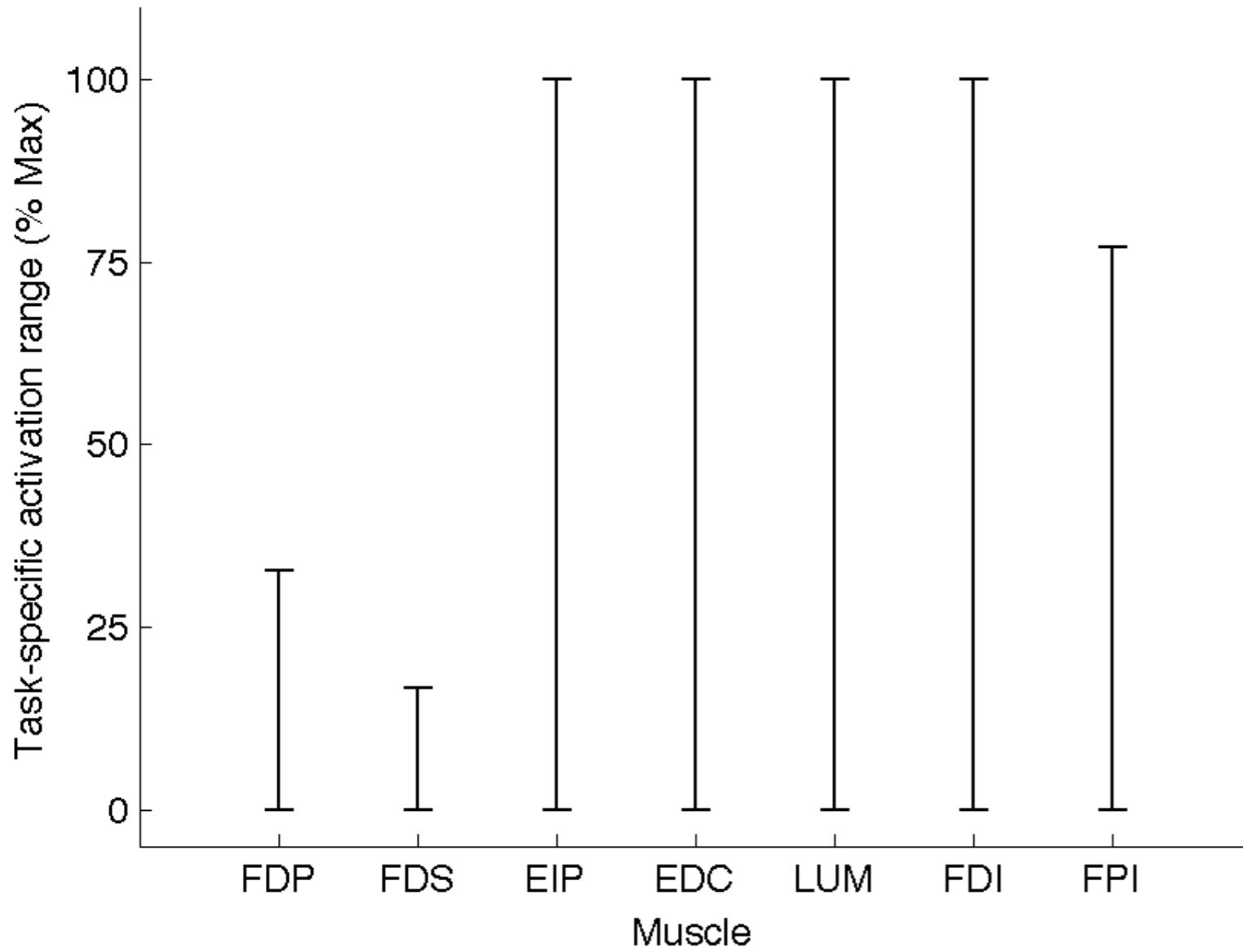
Background

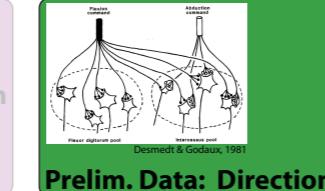
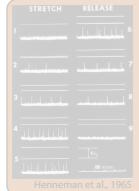


New Approach



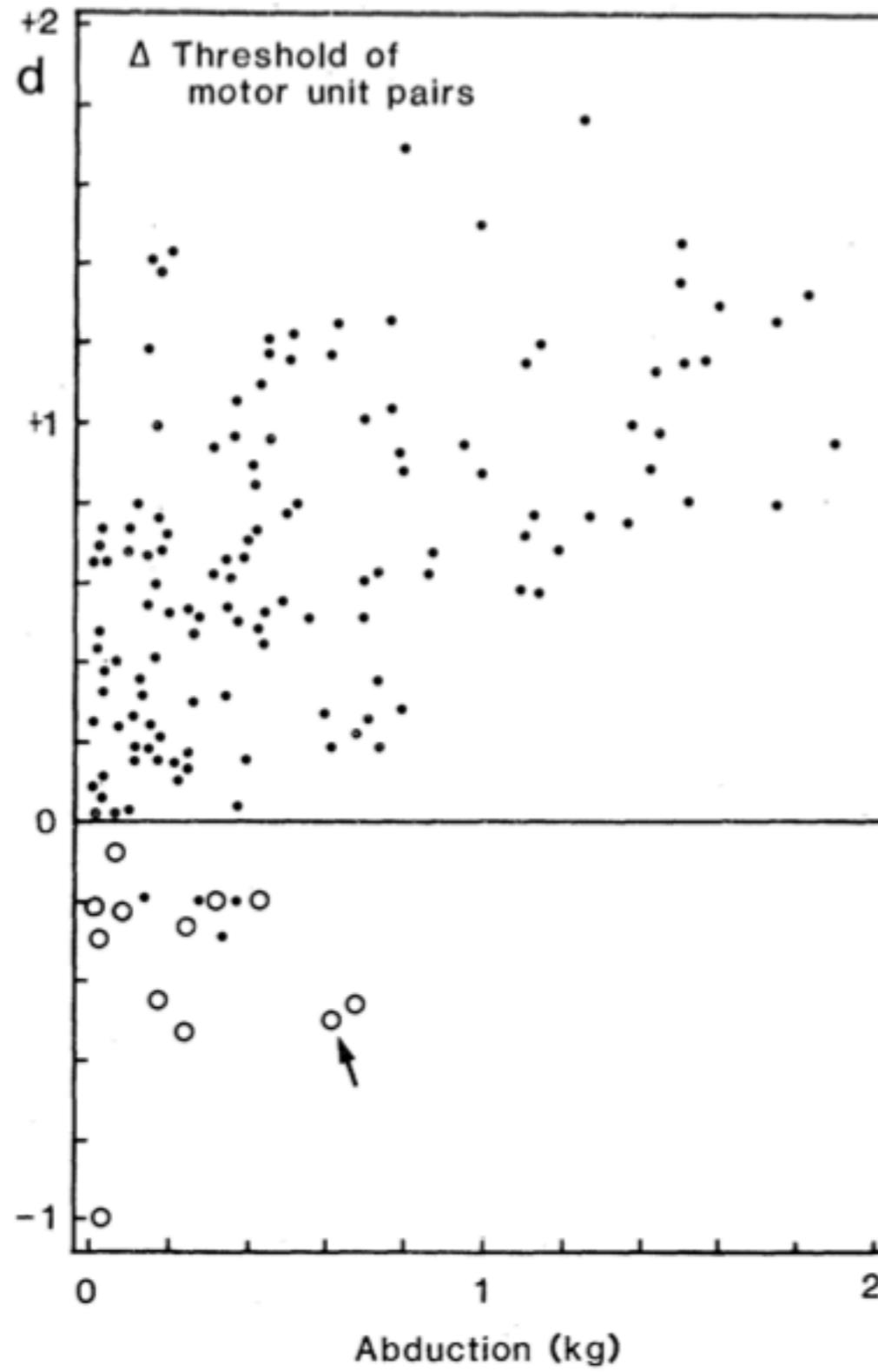
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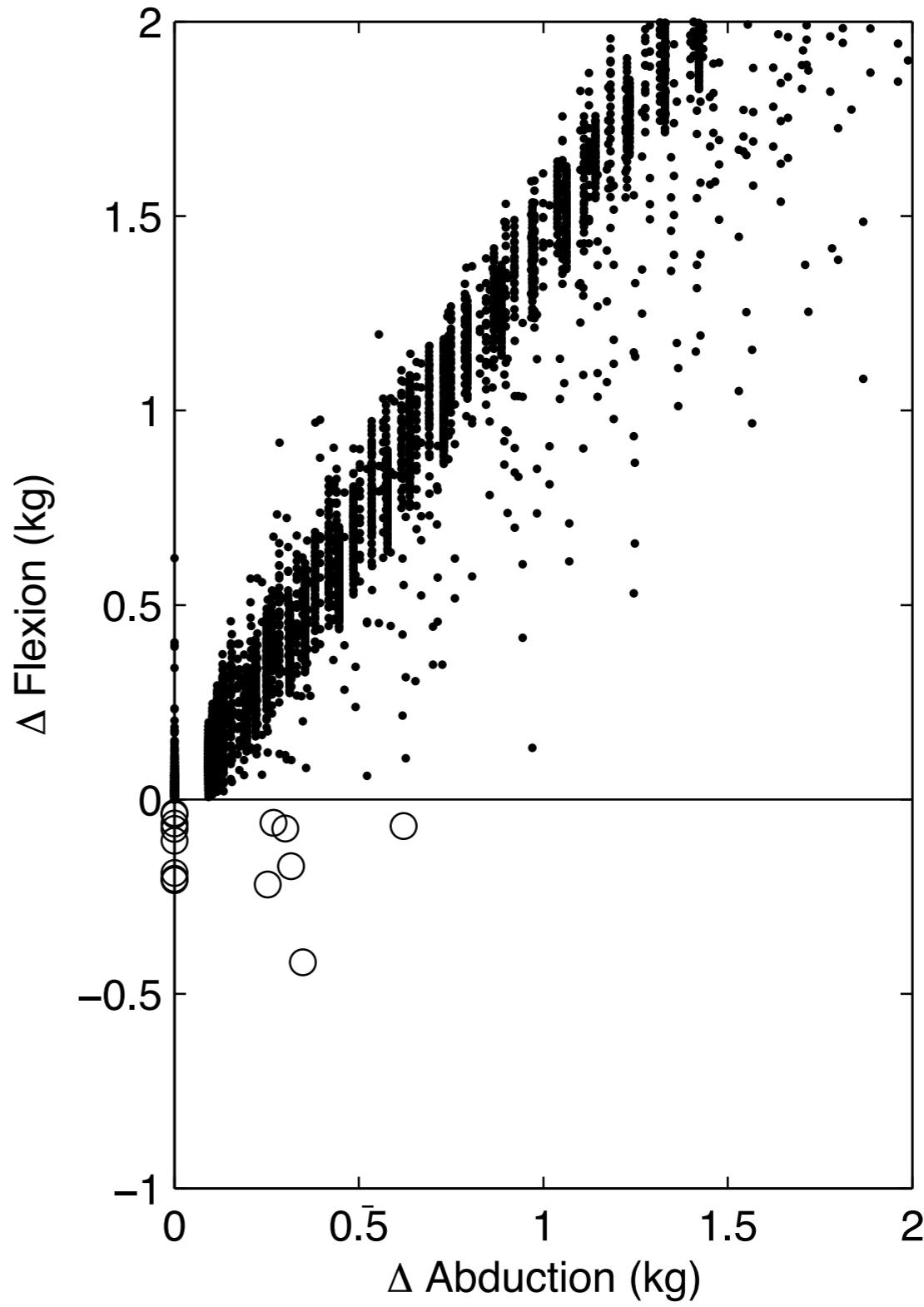


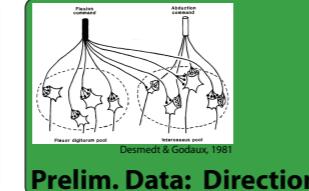
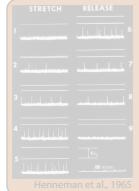
Recruitment reversals

Desmedt & Godaux Data



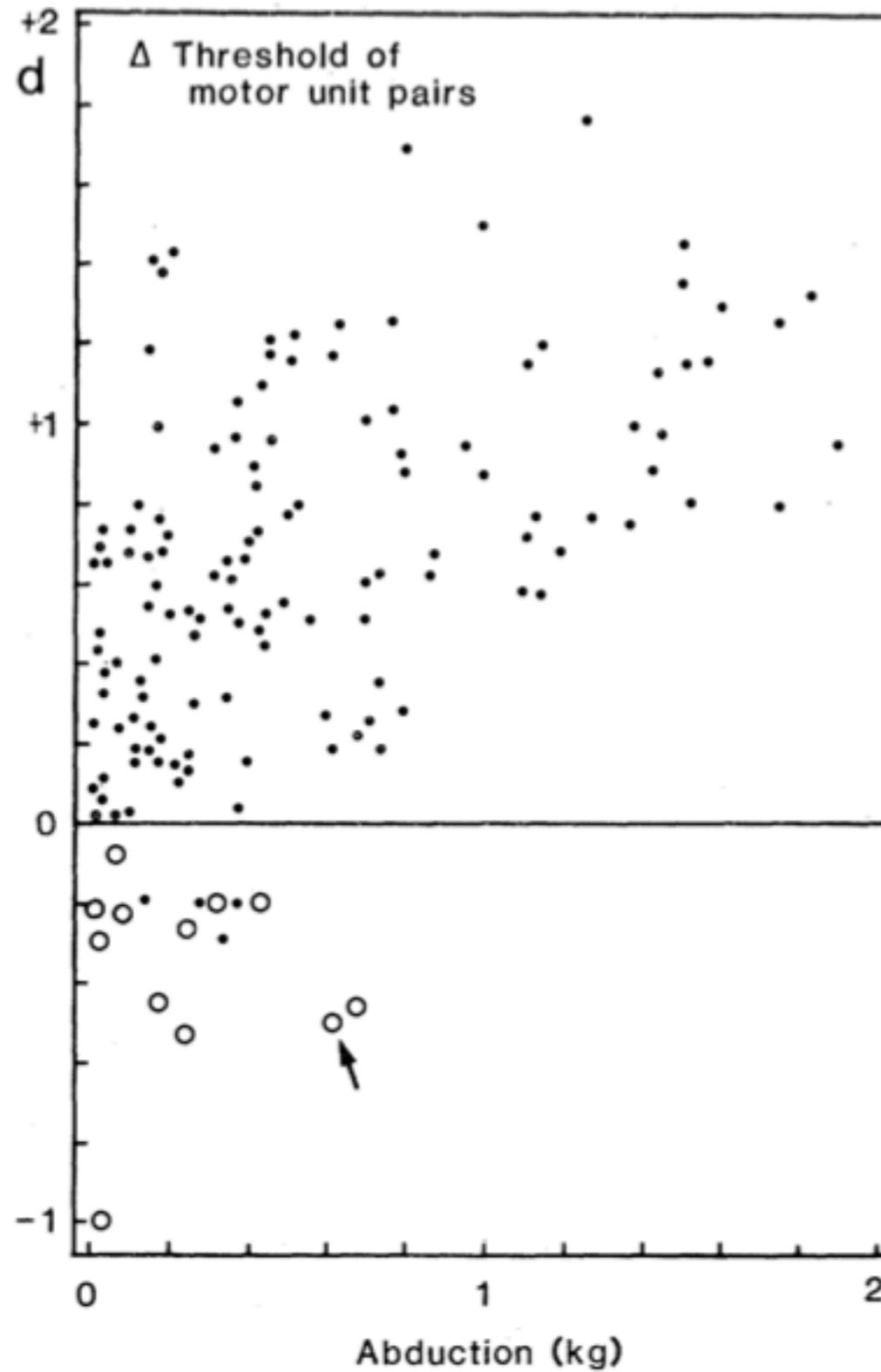
Synaptic modification for noise





Recruitment reversals

Desmedt & Godaux Data



Synaptic modification for noise

