Zusammenspiel elektrischer Stimuli mit sensorischen und motorischen Neuronen oder mit Muskelfasern aus technisch physiologischer Sicht - Möglichkeiten und Grenzen

GESET, Koblenz, 2022

MEDIZINISCHE UNIVERSITÄT WIEN

Winfried Mayr

Center for Medical Physics and Biomedical Engineering

INTERFACING NEURONS AND MUSCLES

with Functional Electrical Stimulation / Neuromodulation

Afferent Nerves

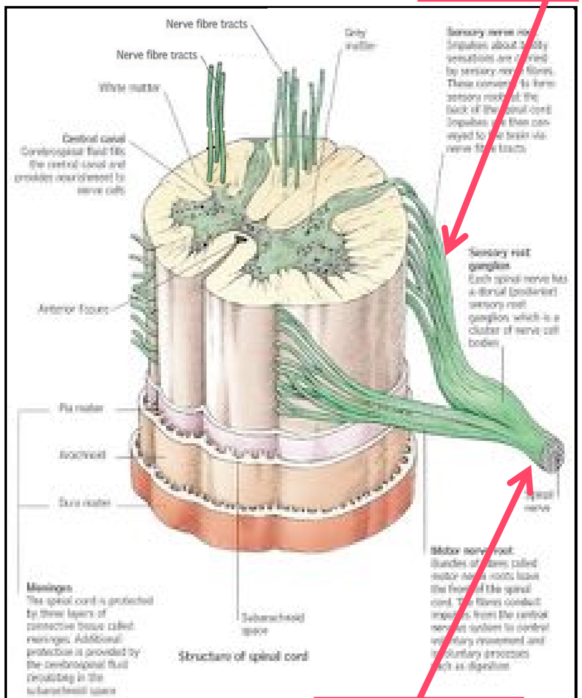
Efferent Nerves

Muscle Fibers

Sensory Functions

Motor Functions

Afferent nerves



Direct Control

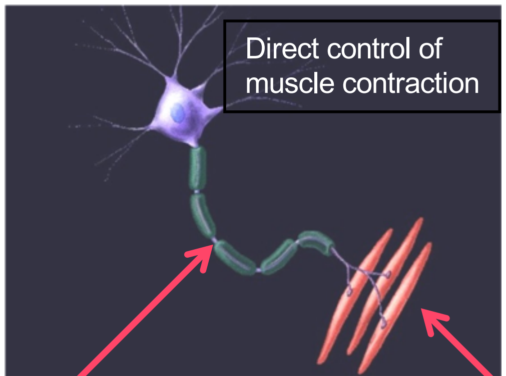
Indirect Control

Spasticity / Stiffness / Pain

Motor Control / Tissue Preservation

Conditioning, Training

Substitution of Functions

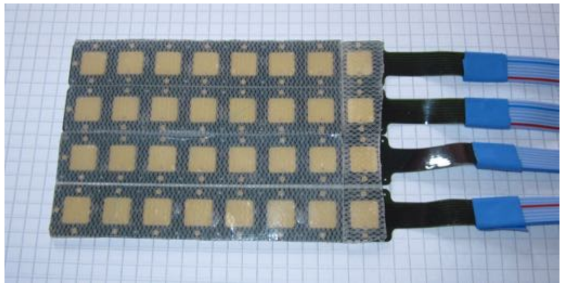


Neuromuscular - motor nerve

Denervated muscle

Mixed Nerve

Electrode-tissue interface - Shape and size of stimuli



noninvasive

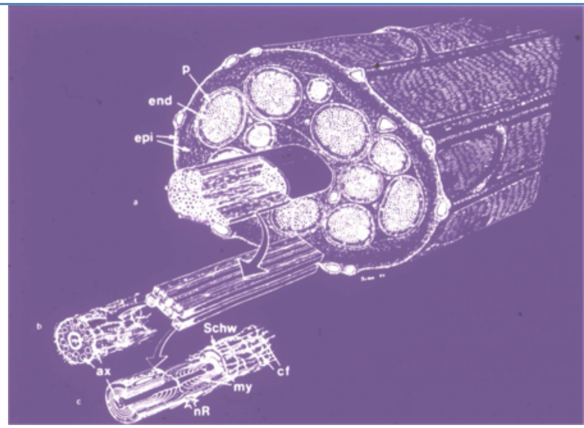
Decisive and limiting compromise on selectivity and safety

*

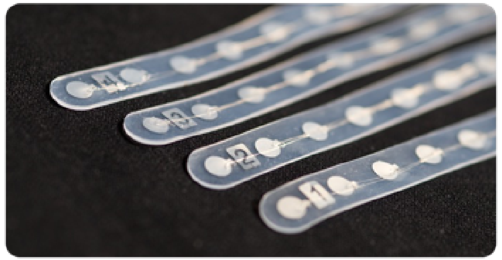
Generally coarse tool to activate tiny structures

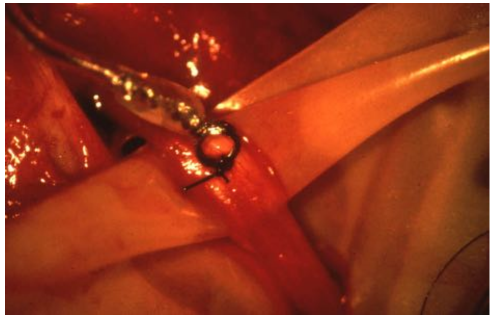
*

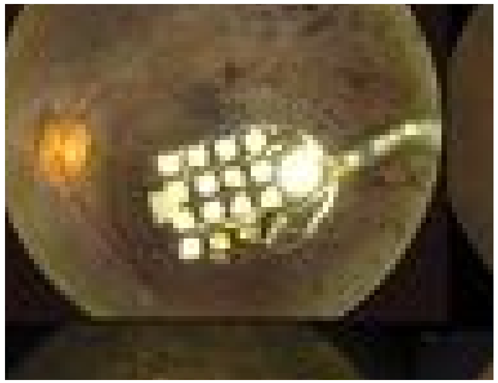
Integration of medical, physiological and engineering expertise



implanted



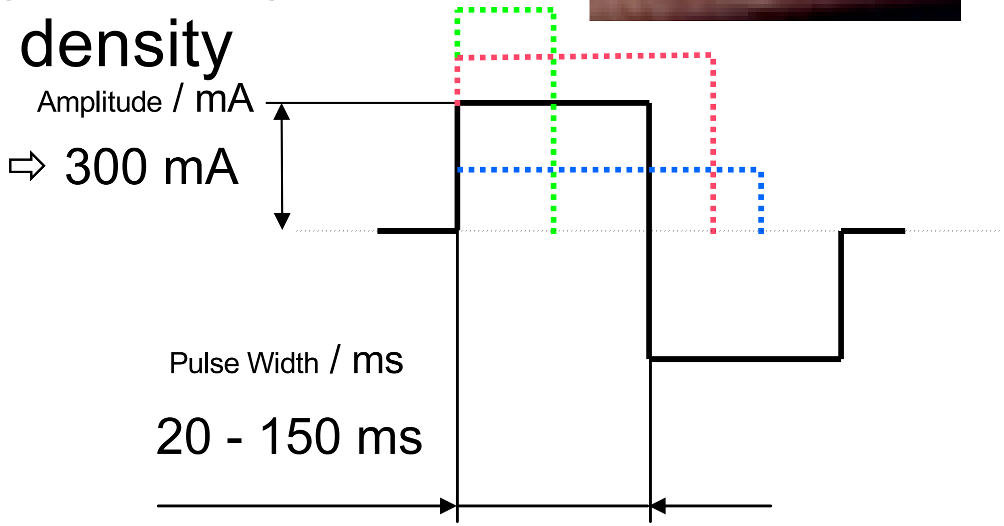


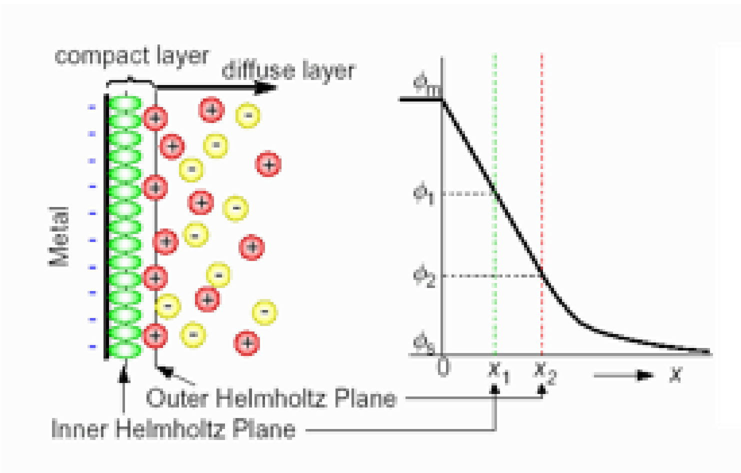


Electrode-tissue interface

Amplitude (mA) **x** Impulse width (ms) **=** Impulse charge (C)

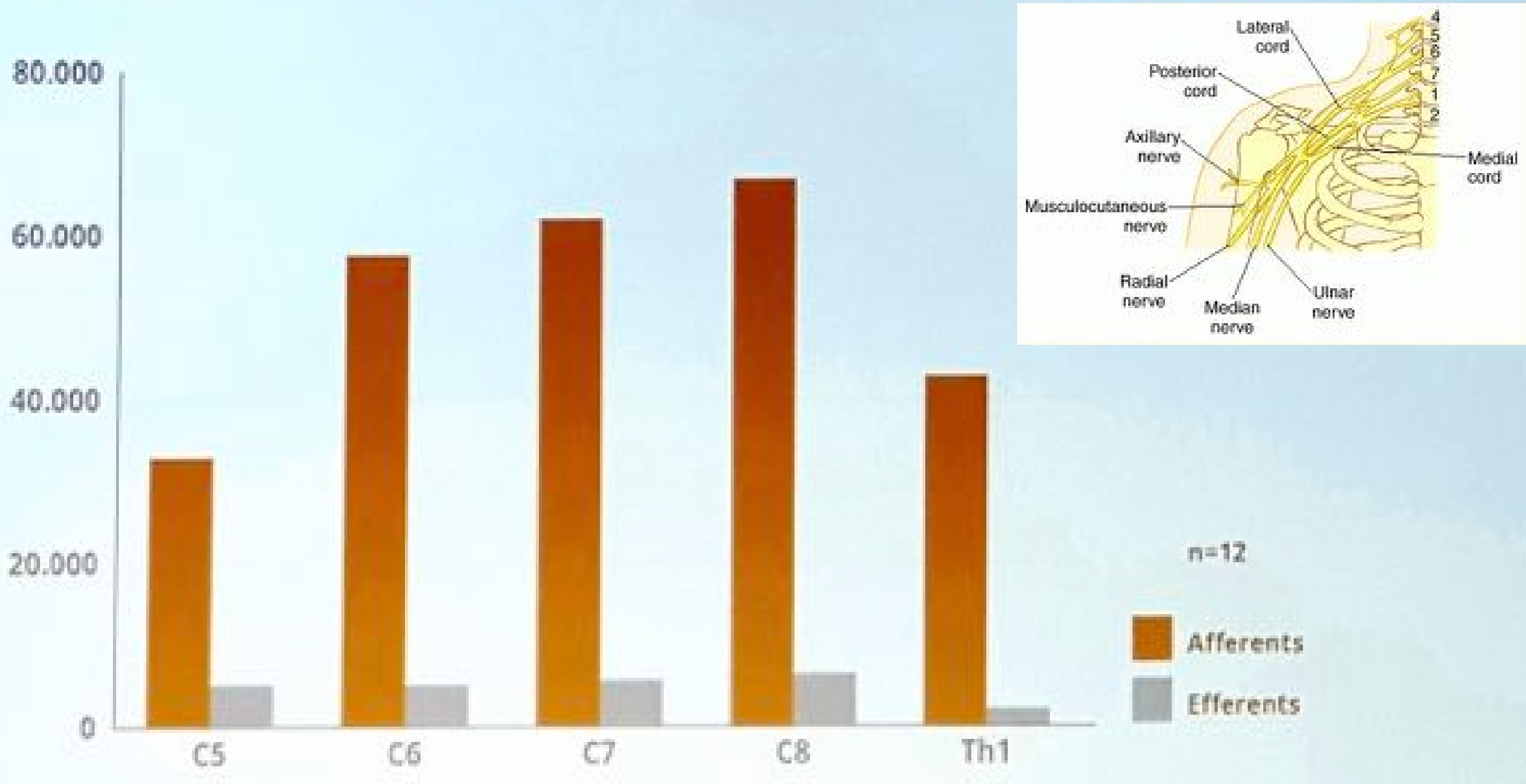
- No DC !
  positive and negative impulse phase equal
- Impulse charge / Electrode contact surface
  <u>must not exceed</u> Charge Injection Limit
  in $\mu C/cm^2$ ($\mu As/cm^2$)
- Risk: excessive local current density





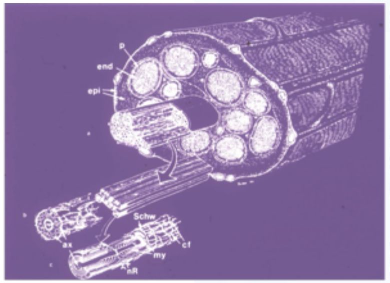
Imp. charge ⇨ 6.000 µAs (⇨ 45.000 µAs)	
200 cm^2	⇨ 30 $\mu C/cm^2$ (⇨ 225 $\mu C/cm^2$)

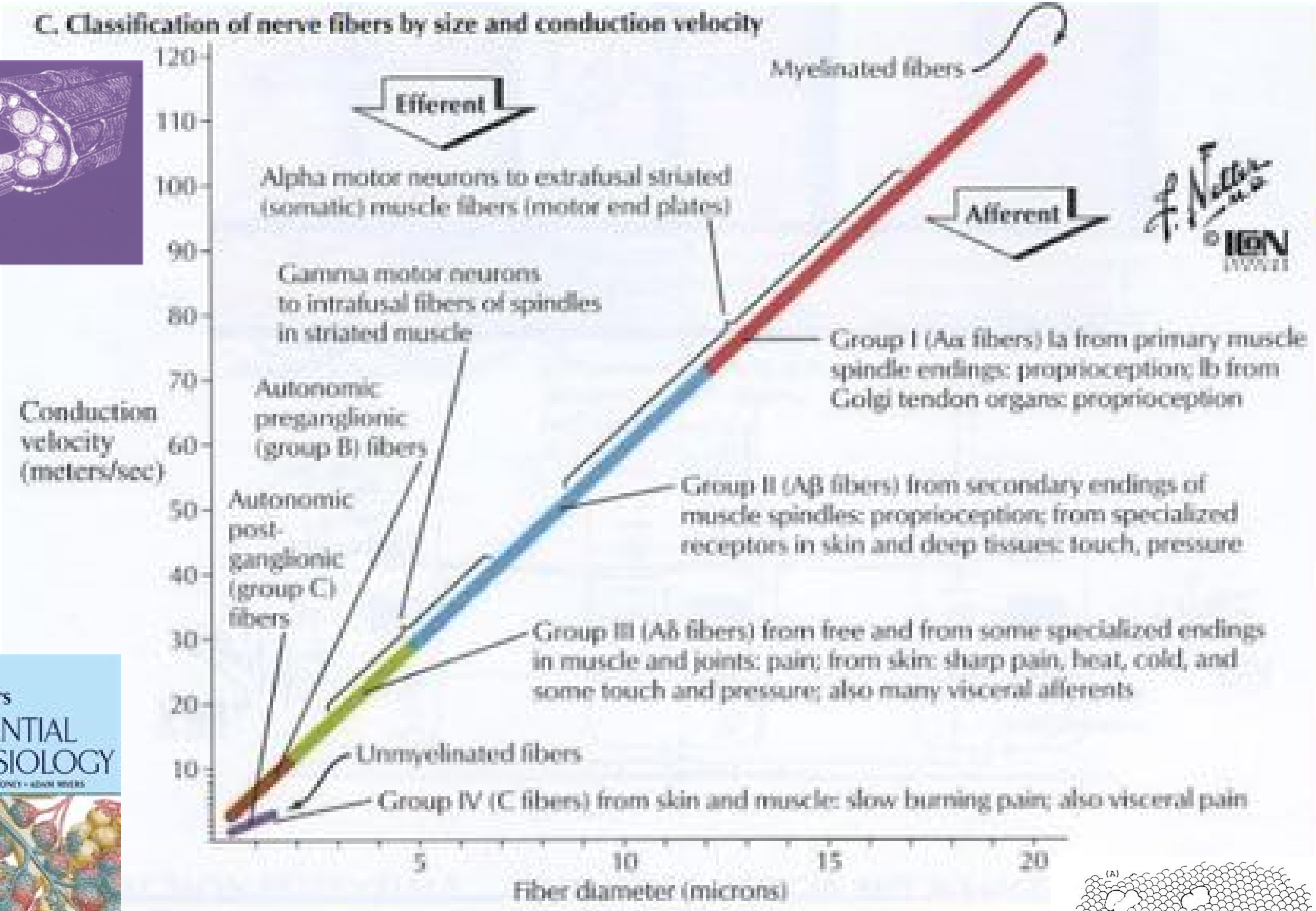
FIRST QUANTITATIVE **DATA ON HUMAN BP**

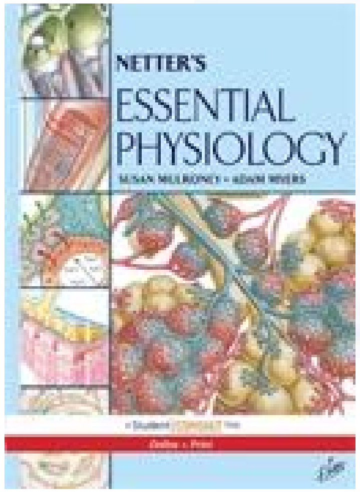


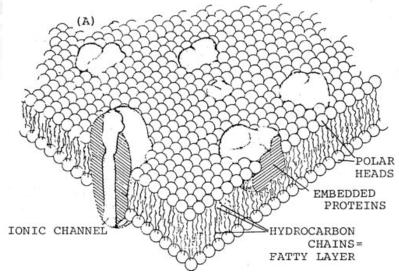
afferent – efferent
9 : 1

Gesslbauer B, et al.
Axonal components of nerves innervating the human arm.
Ann Neurol. 2017 Sep;82(3):396-408

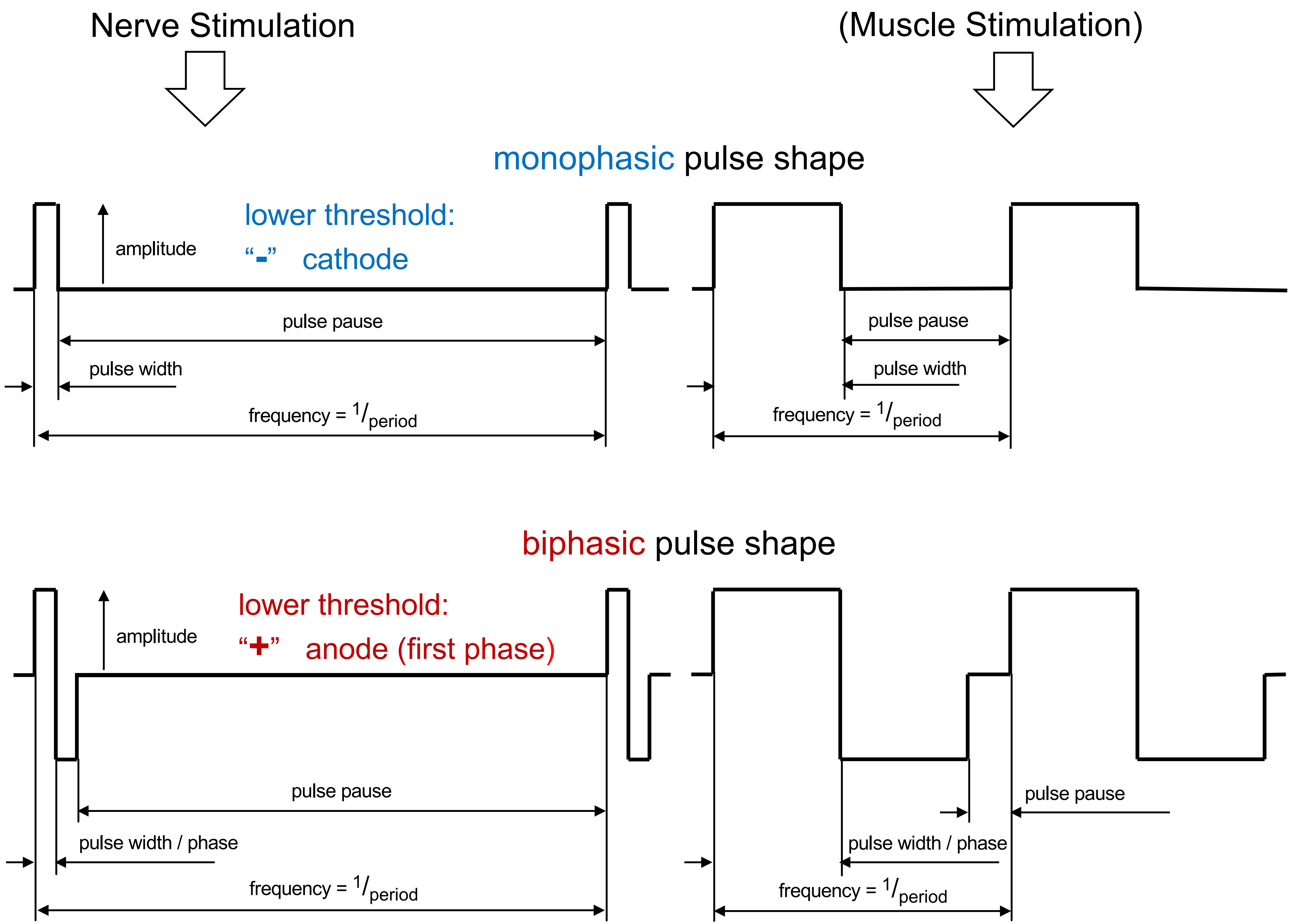




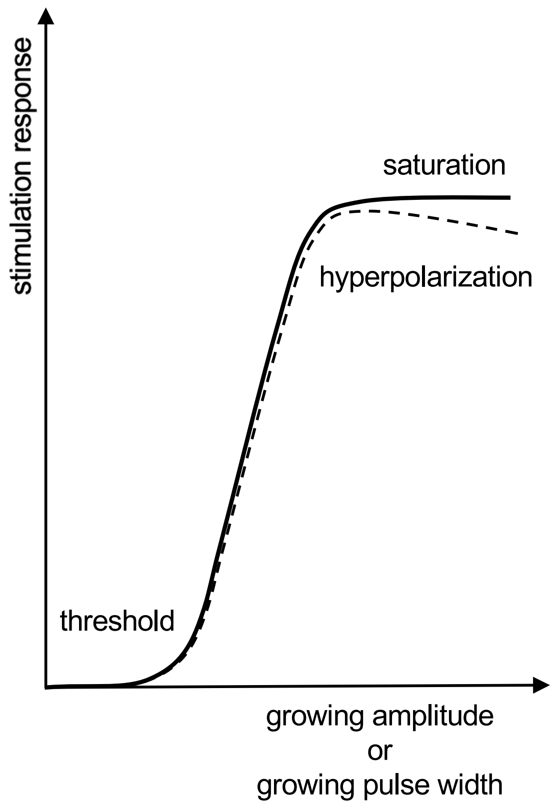




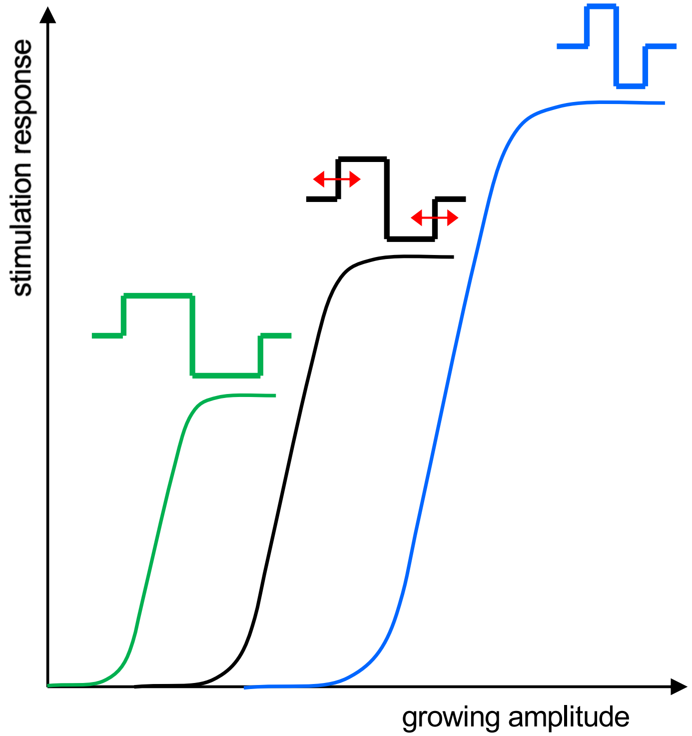
Bretscher M.S. and Raff M.C. 1975. Mammalian plasma membranes. Nature 258, 43-49



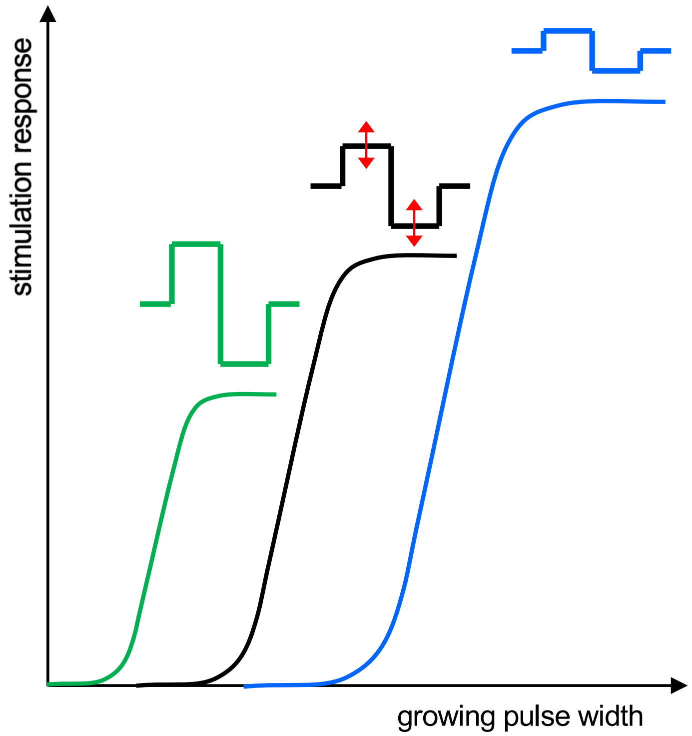
Nerve Stimulation
(Muscle Stimulation)
monophasic pulse shape
amplitude
lower threshold:
"-" cathode
pulse pause
pulse width
frequency = 1/period
pulse pause
pulse width
frequency = 1/period
biphasic pulse shape
amplitude
lower threshold:
"+" anode (first phase)
pulse pause
pulse width / phase
frequency = 1/period
pulse pause
pulse width / phase
frequency = 1/period



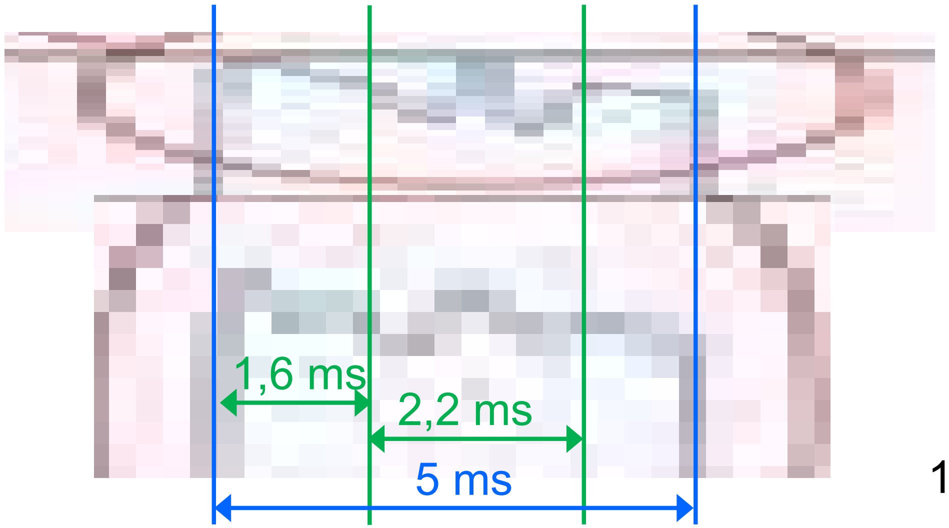
typical recruitment curve,
threshold to saturation

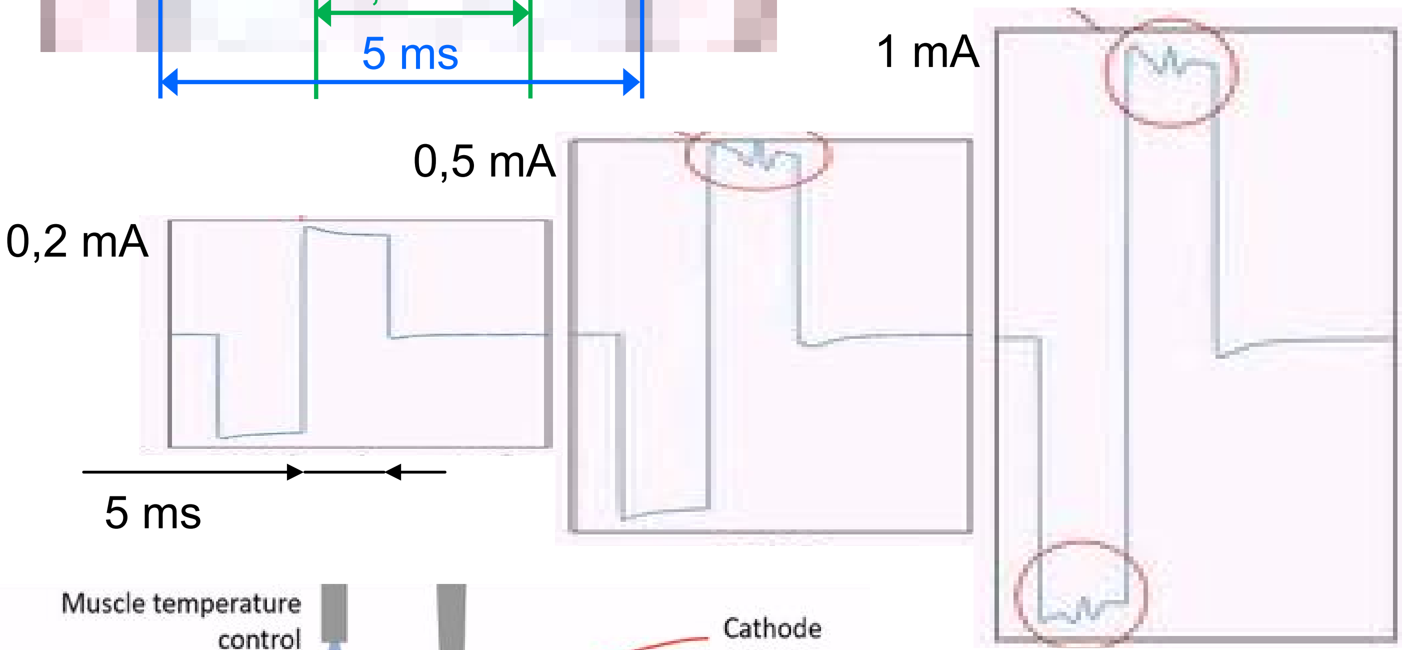


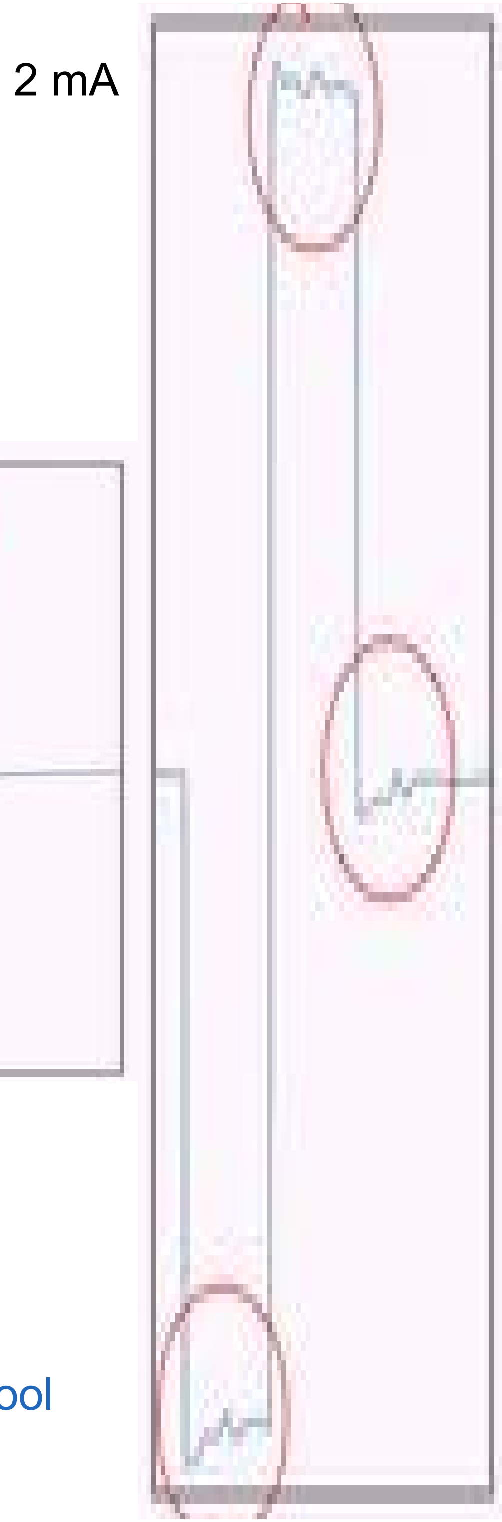
typical recruitment curve,
amplitude variation, constant pulse width

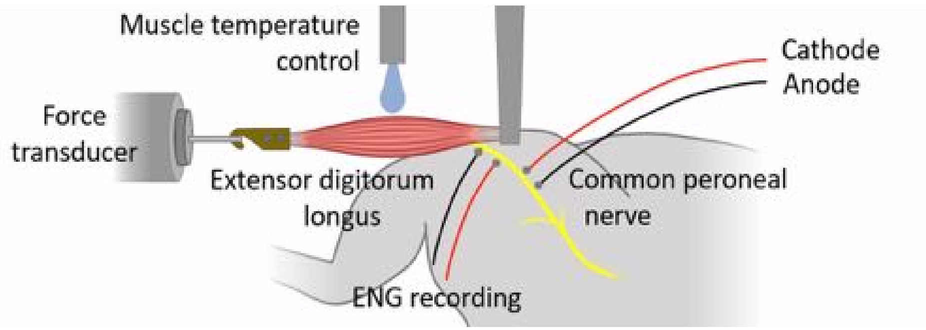


typical recruitment curve,
pulse width variation, constant amplitude

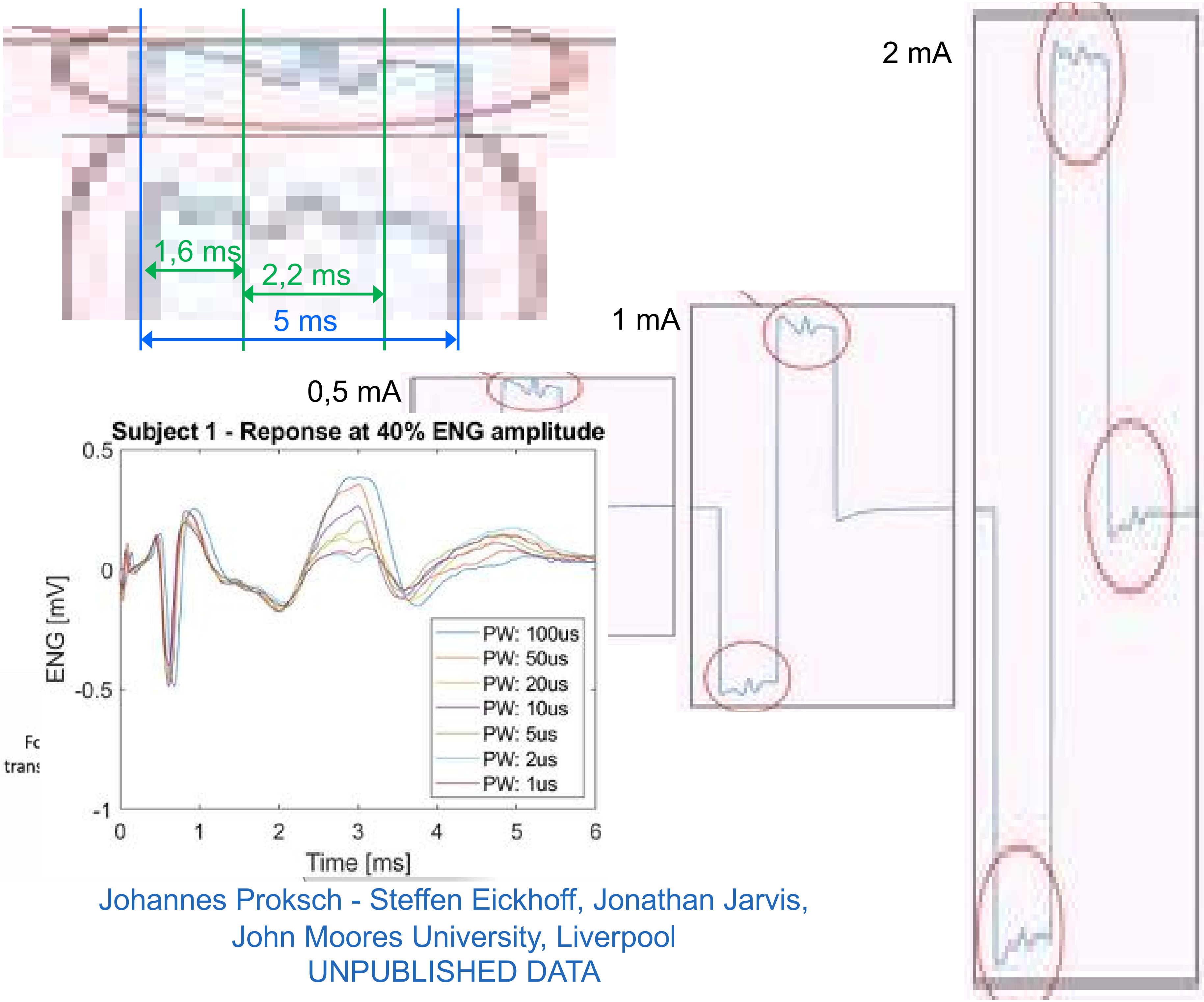






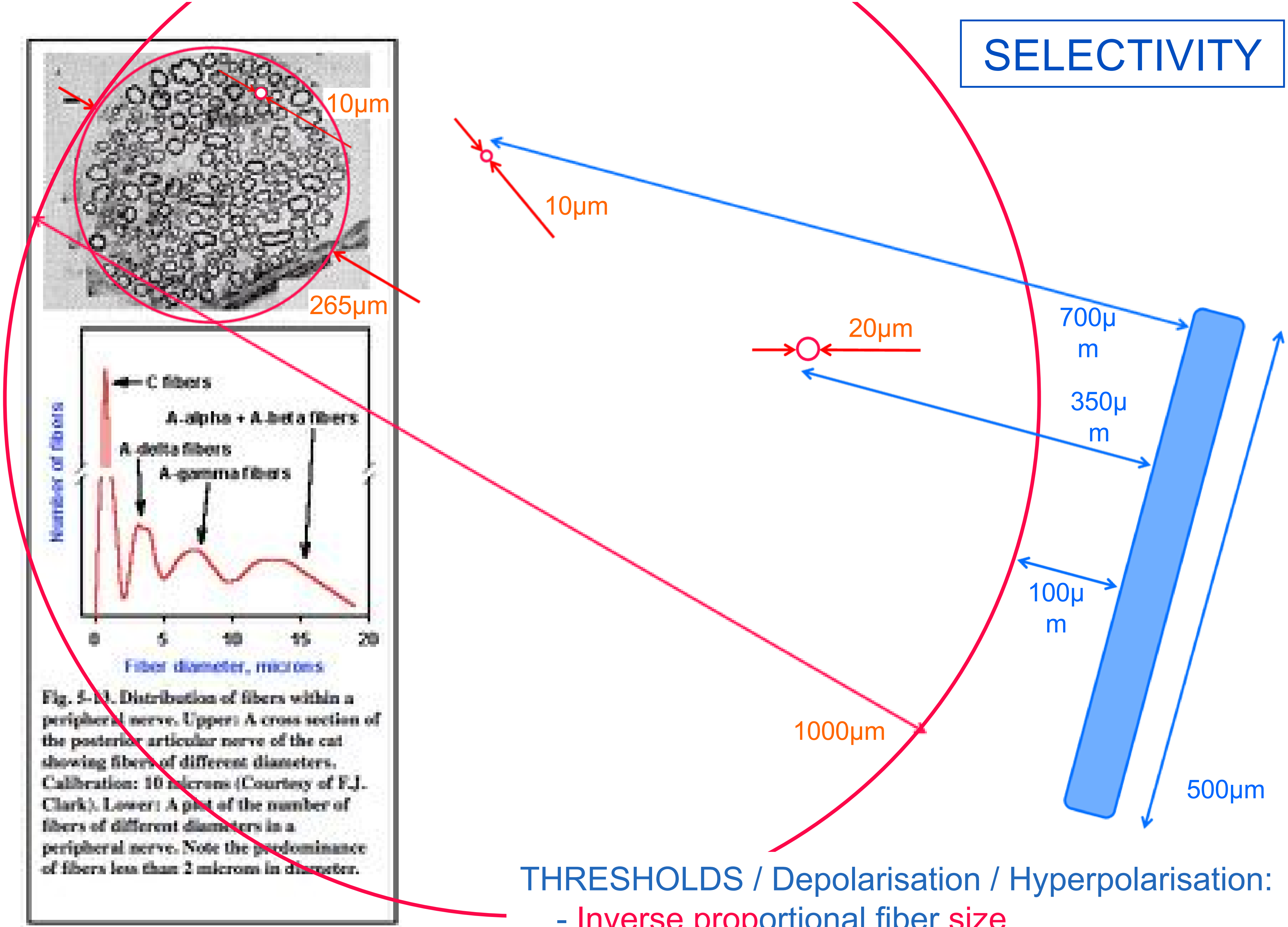


Steffen Eickhoff, Jonathan Jarvis – John Moores University, Liverpool
UNPUBLISHED DATA



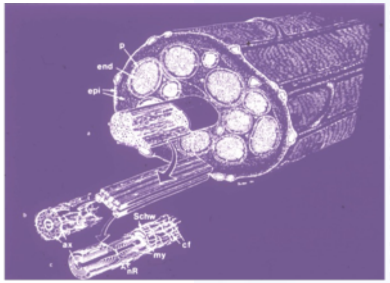
Johannes Proksch - Steffen Eickhoff, Jonathan Jarvis,
John Moores University, Liverpool
UNPUBLISHED DATA

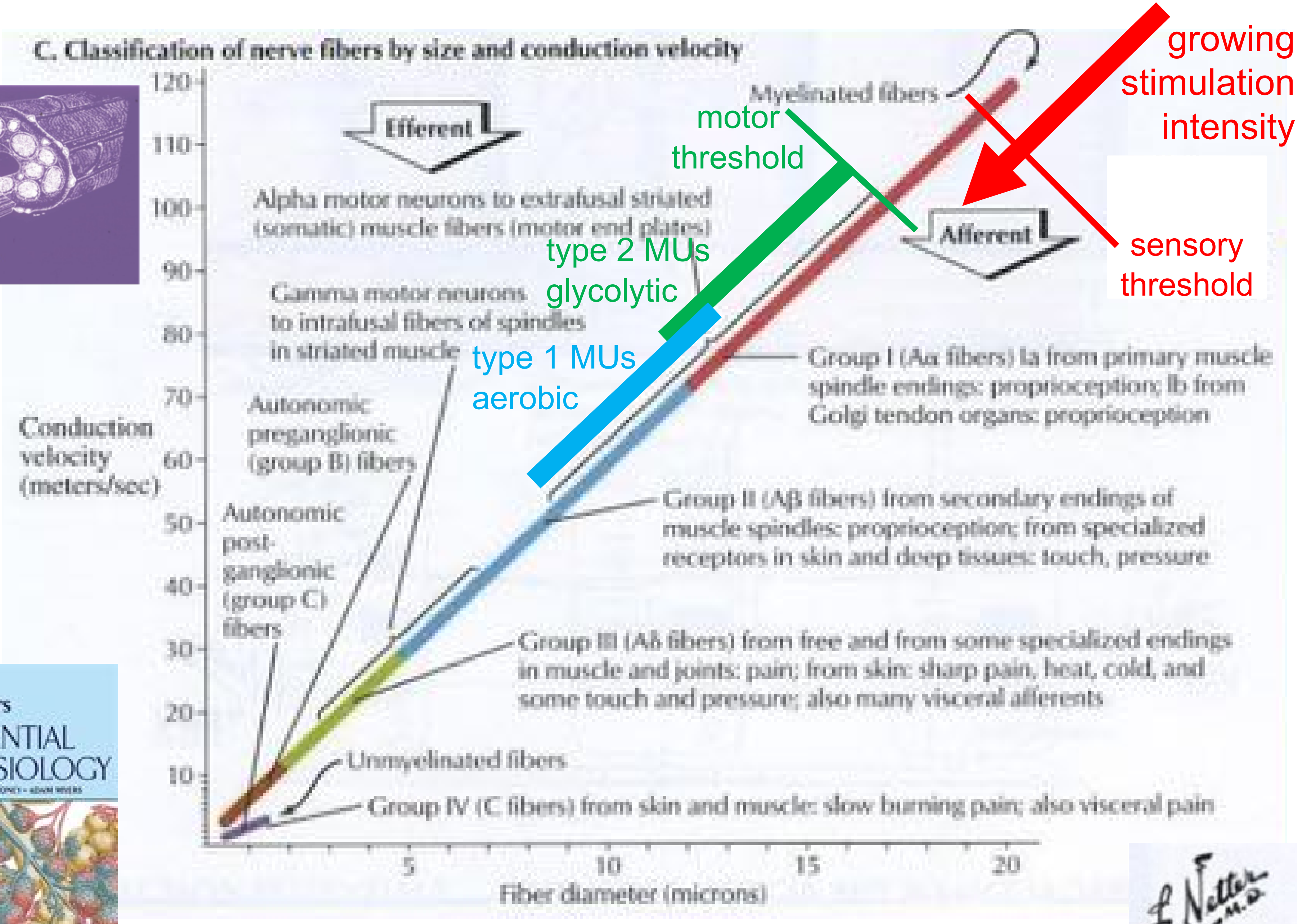
SELECTIVITY



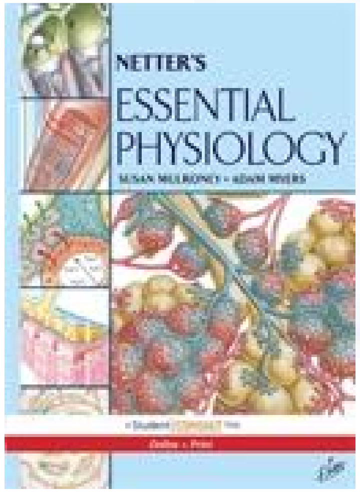
THRESHOLDS / Depolarisation / Hyperpolarisation:

- Inverse proportional fiber size
- Prop. to square of distance



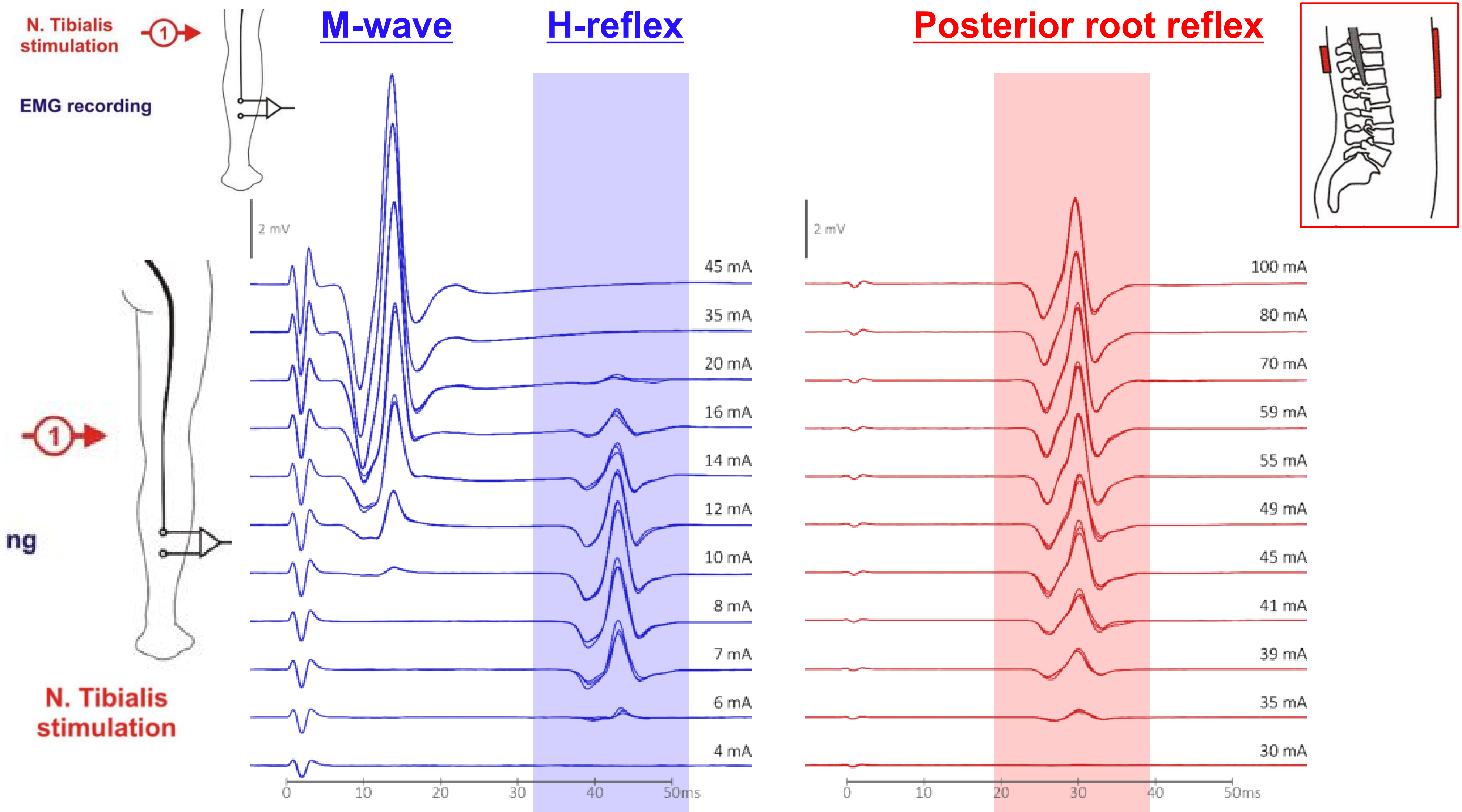


C. Classification of nerve fibers by size and conduction velocity
Efferent
Afferent
Myelinated fibers
Alpha motor neurons to extrafusal striated (somatic) muscle fibers (motor end plates)
Gamma motor neurons to intrafusal fibers of spindles in striated muscle
Autonomic preganglionic (group B) fibers
Autonomic post-ganglionic (group C) fibers
Group I (Aα fibers) Ia from primary muscle spindle endings: proprioception; Ib from Golgi tendon organs: proprioception
Group II (Aβ fibers) from secondary endings of muscle spindles: proprioception; from specialized receptors in skin and deep tissues: touch, pressure
Group III (Aδ fibers) from free and from some specialized endings in muscle and joints: pain; from skin: sharp pain, heat, cold, and some touch and pressure; also many visceral afferents
Unmyelinated fibers
Group IV (C fibers) from skin and muscle: slow burning pain; also visceral pain
Conduction velocity (meters/sec)
Fiber diameter (microns)
120
110
100
90
80
70
60
50
40
30
20
10
5
10
15
20
growing stimulation intensity
motor threshold
sensory threshold
type 2 MUs glycolytic
type 1 MUs aerobic

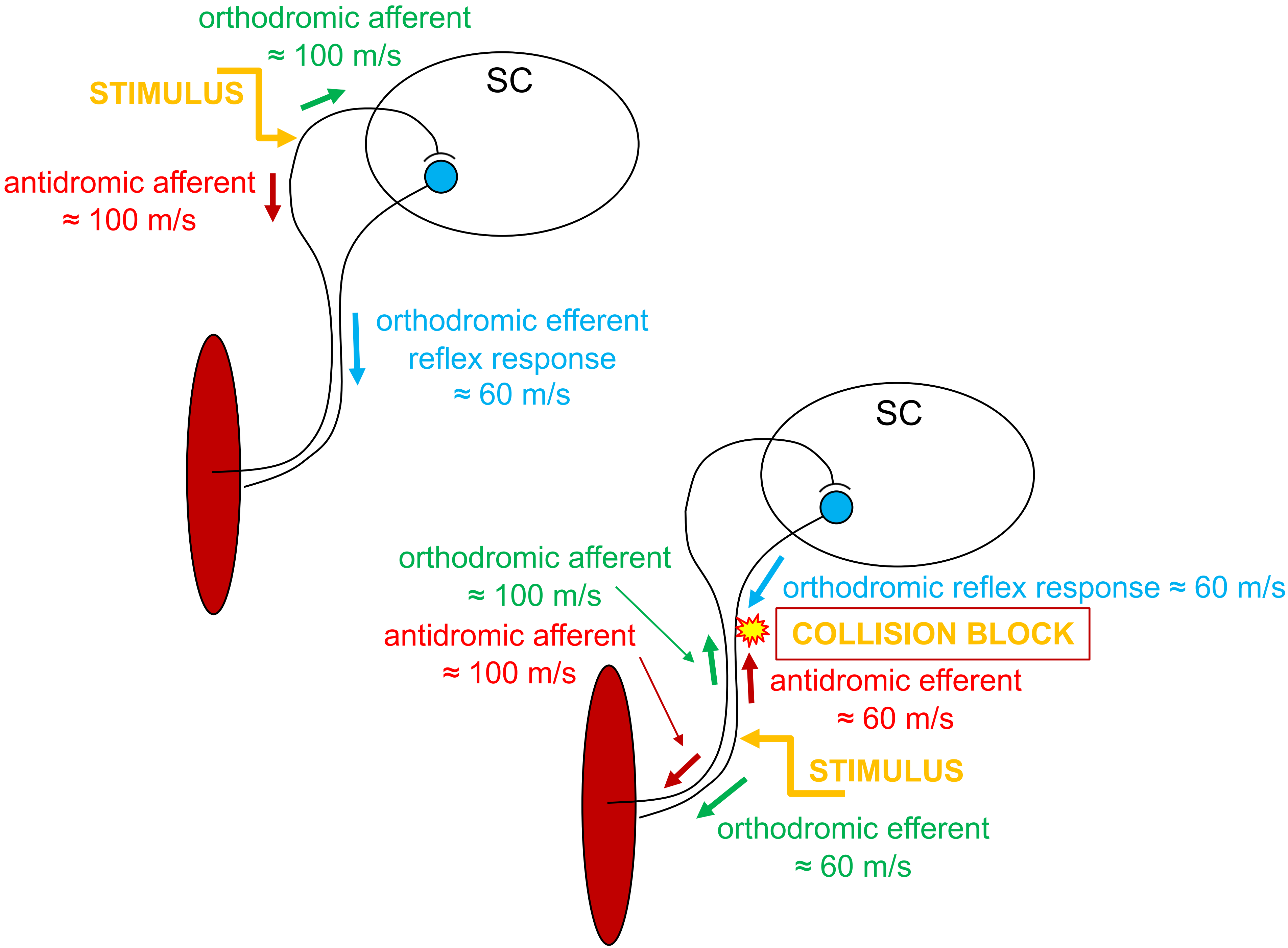


NETTER'S
ESSENTIAL PHYSIOLOGY

H-reflex and posterior root reflex in the soleus muscle



by Matthias Krenn



orthodromic afferent
≈ 100 m/s
STIMULUS
SC
antidromic afferent
≈ 100 m/s
orthodromic efferent
reflex response
≈ 60 m/s
SC
orthodromic afferent
≈ 100 m/s
orthodromic reflex response ≈ 60 m/s
COLLISION BLOCK
antidromic afferent
≈ 100 m/s
antidromic efferent
≈ 60 m/s
STIMULUS
orthodromic efferent
≈ 60 m/s

If we have an idea on fiber recruitment –

- what about neural processing / control of movement ?

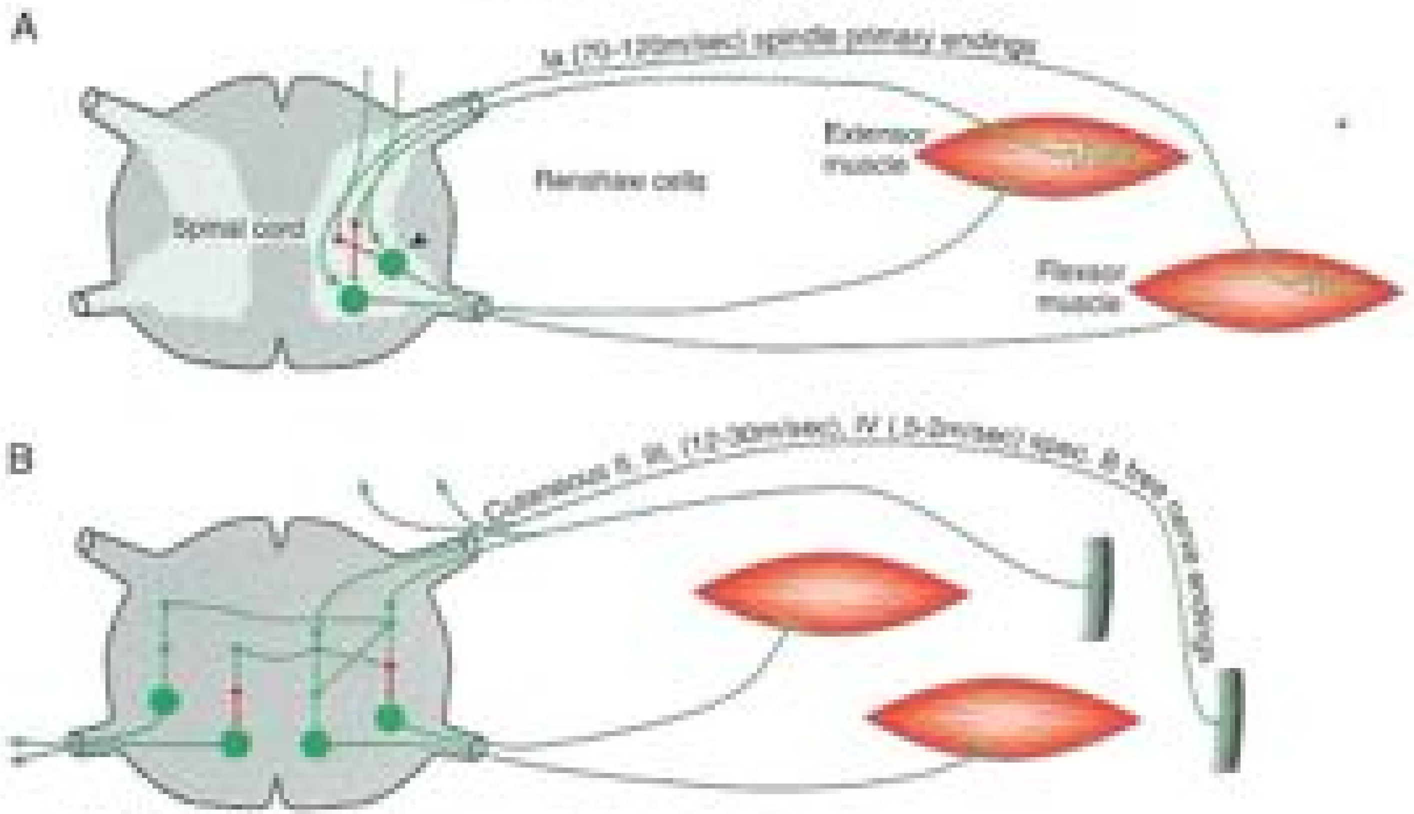


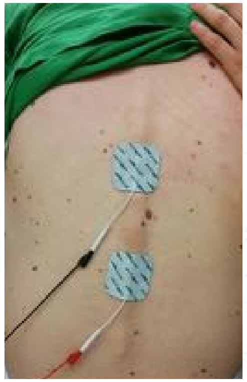
FIGURE 29.3 Circuitry for segmental spinal reflexes. Ia spindle reflexes are activated by stretch of the muscle and cause excitation of that muscle and its synergists and reciprocal inhibition of its antagonists. Skin reflexes (activated by a noxious stimulus) may cause withdrawal of the limb away from the stimulus with a supporting reaction in the opposite limb. Adapted from Thach and Montgomery, *Neurobiology of Disease*, Oxford University Press, New York, 1990.

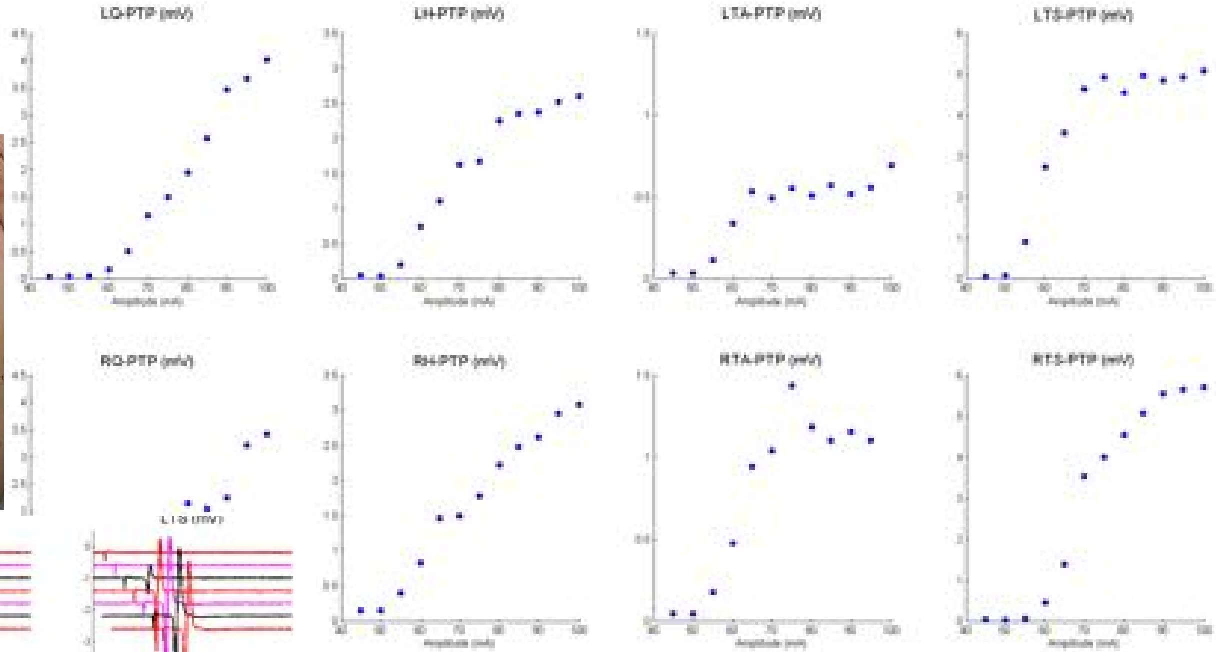
Electrical stimulation of peripheral nerves or posterior roots can activate monosynaptic and polysynaptic reflex arcs

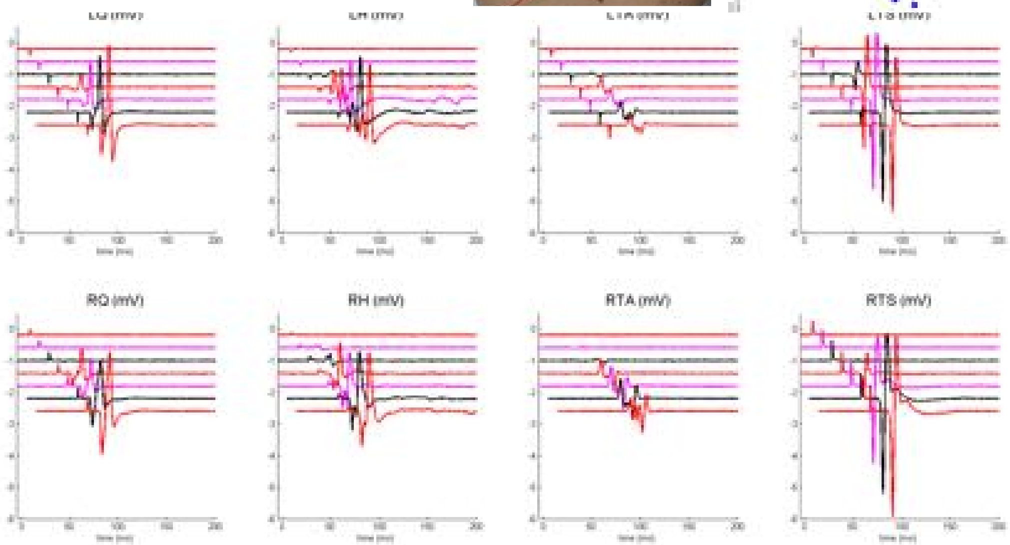
WWTF

LS11-057

Augmentation of residual neural control by non-invasive spinal cord stimulation to modify spasticity in spinal cord injured people

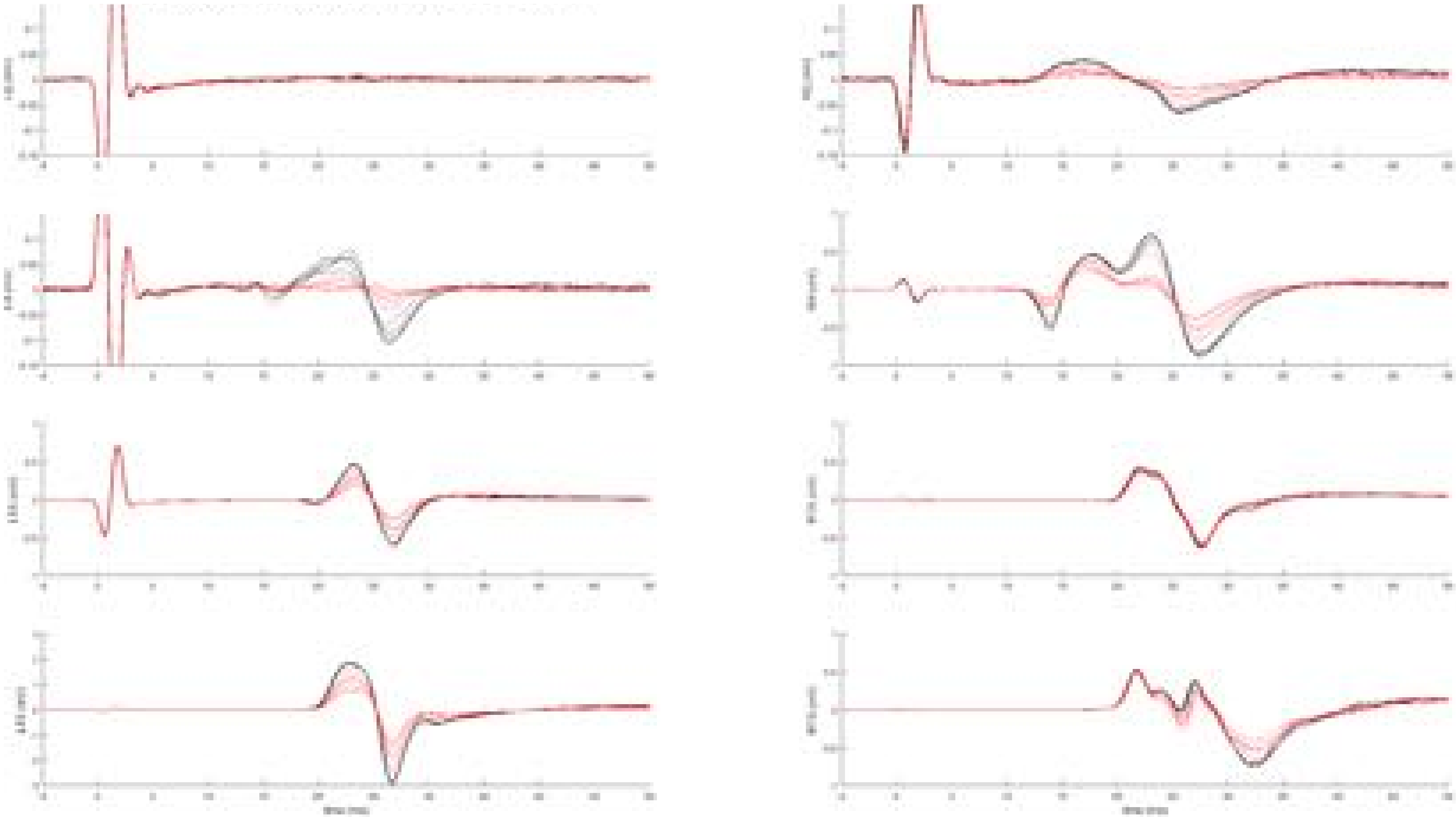






Posterior root reflex as marker for discompleteness

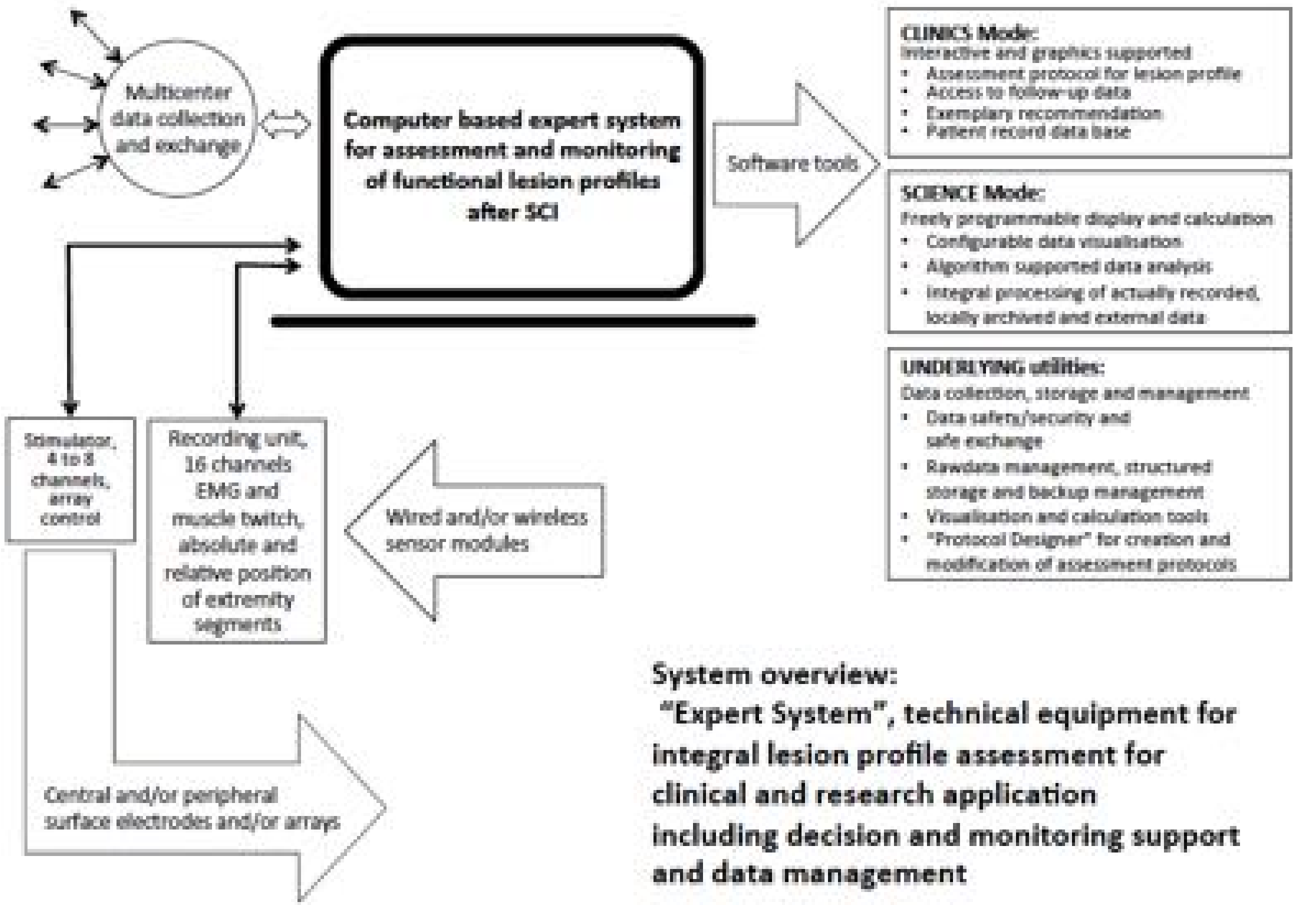
Modification of posterior root reflexes: Attempt to extend both legs (red), control (black)



LS11-057

Augmentation of residual neural control by non-invasive spinal cord stimulation to modify spasticity in spinal cord injured people

- BMCA
  - Reinforcement Maneuvers
  - Volitional Maneuvers
  - Passive Maneuvers
  - Reflex Modulation
- Bipolar Non-Invasive SCS
  - Recruitment curve
  - Frequency sweeps



- Personalization
  (individual profile,
  altered and residual functions)
- Specific
  planning and monitoring

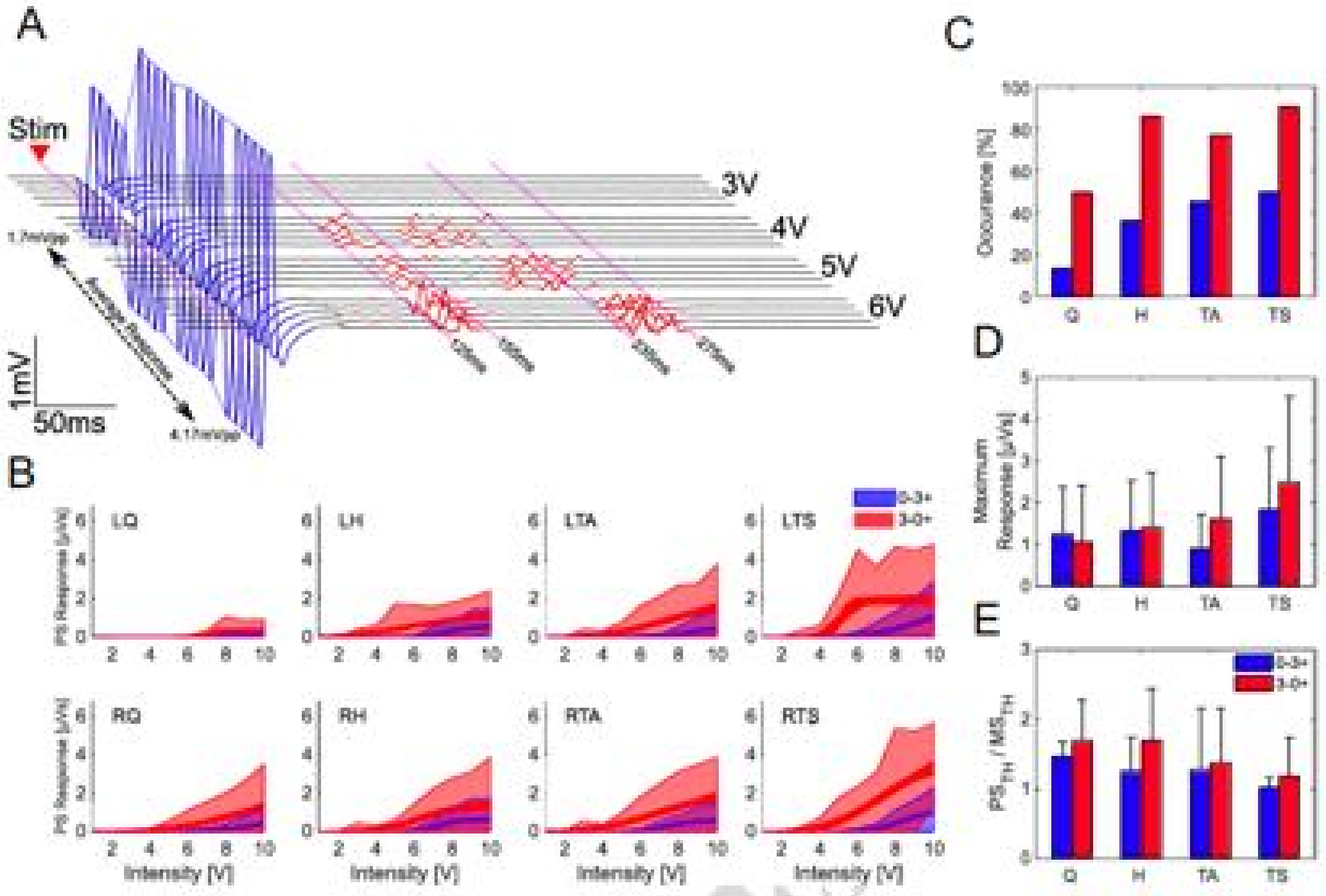
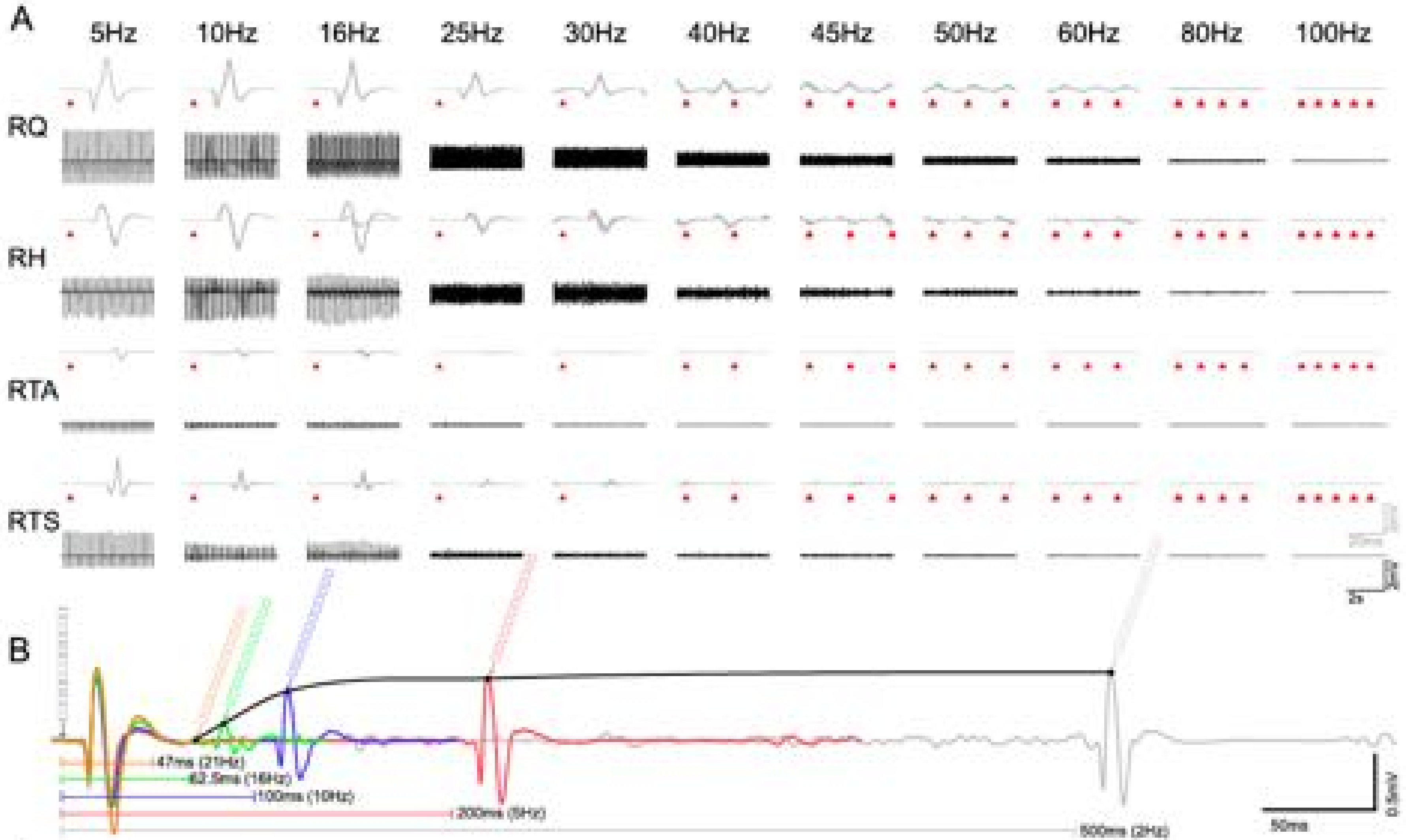
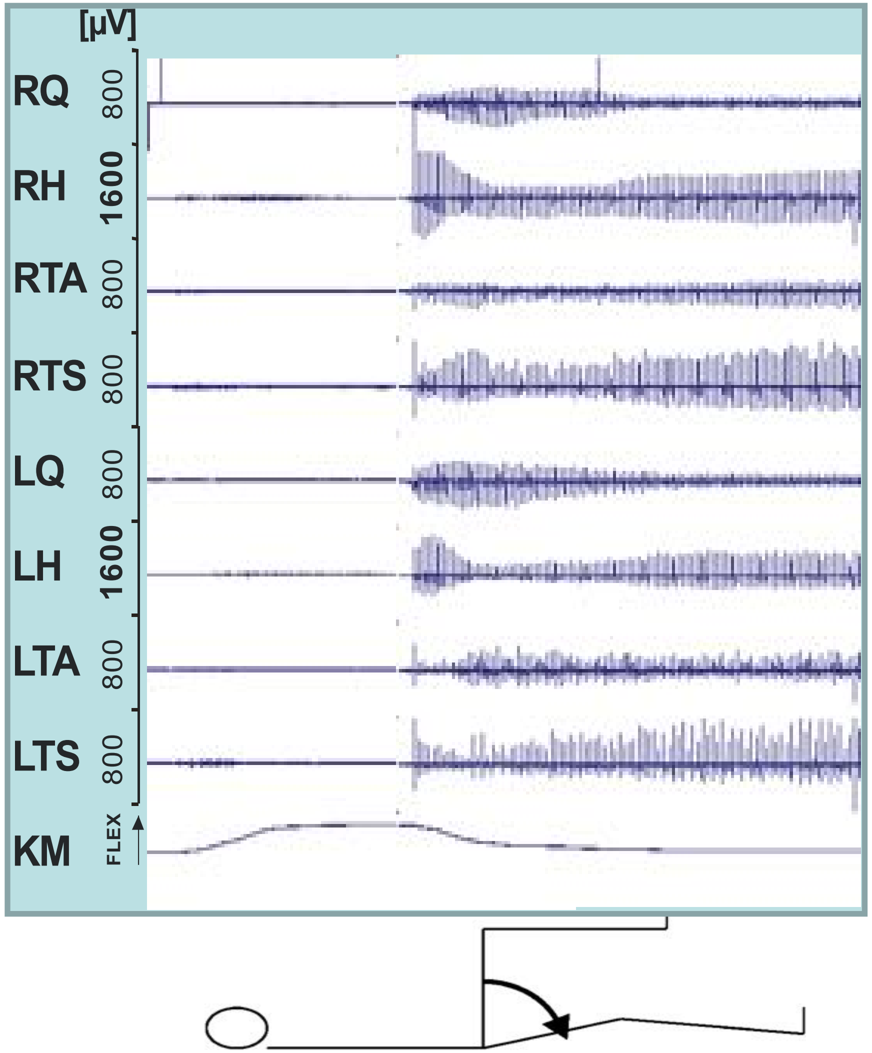


Fig. 2 Characteristics of the Polysynaptic responses. **A** Exemplary responses from RH on SID 10 with 3–0+electrode configuration. The sEMG show in blue the short-latency (monosynaptic) responses, appearing after ~7 ms, and, in red, the long-latency (polysynaptic) responses, which appear in two groups with latencies of around 130 ms and 260 ms. Both types of responses evolve when the stimulus intensity is increased. **B** Estimated recruitment curve for eight subjects (SID2 and SID8 excluded), showing the 95% confidence interval for the mean amplitude (narrowband) and standard deviation of the samples at each intensity (shadowed area) for the lower limbs with both electrode configurations. **C** Shows the percentage of polysynaptic activity occurrence on each muscle group (both sides grouped together). **D** shows the mean maximum response for each muscle and electrode configuration (SID8 excluded due to continuous activity not associated with the stimulation). Finally, **E** Shows the relative threshold of the polysynaptic activity compared to the monosynaptic activity

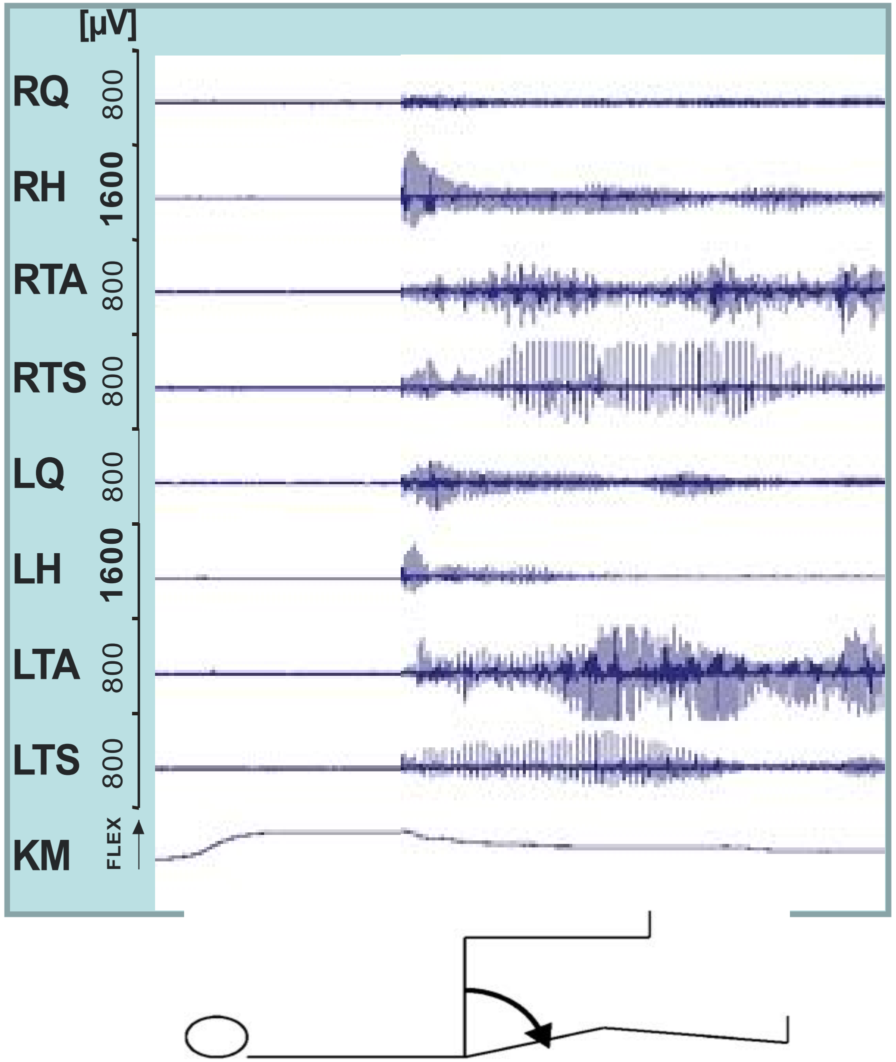

A
5Hz
10Hz
16Hz
25Hz
30Hz
40Hz
45Hz
50Hz
60Hz
80Hz
100Hz
RQ
RH
RTA
RTS
B
47ms (21Hz)
62.5ms (16Hz)
100ms (10Hz)
200ms (5Hz)
500ms (2Hz)
50ms
0.5mV

Effect of altered frequency on passively induced flexion

10V , 10Hz

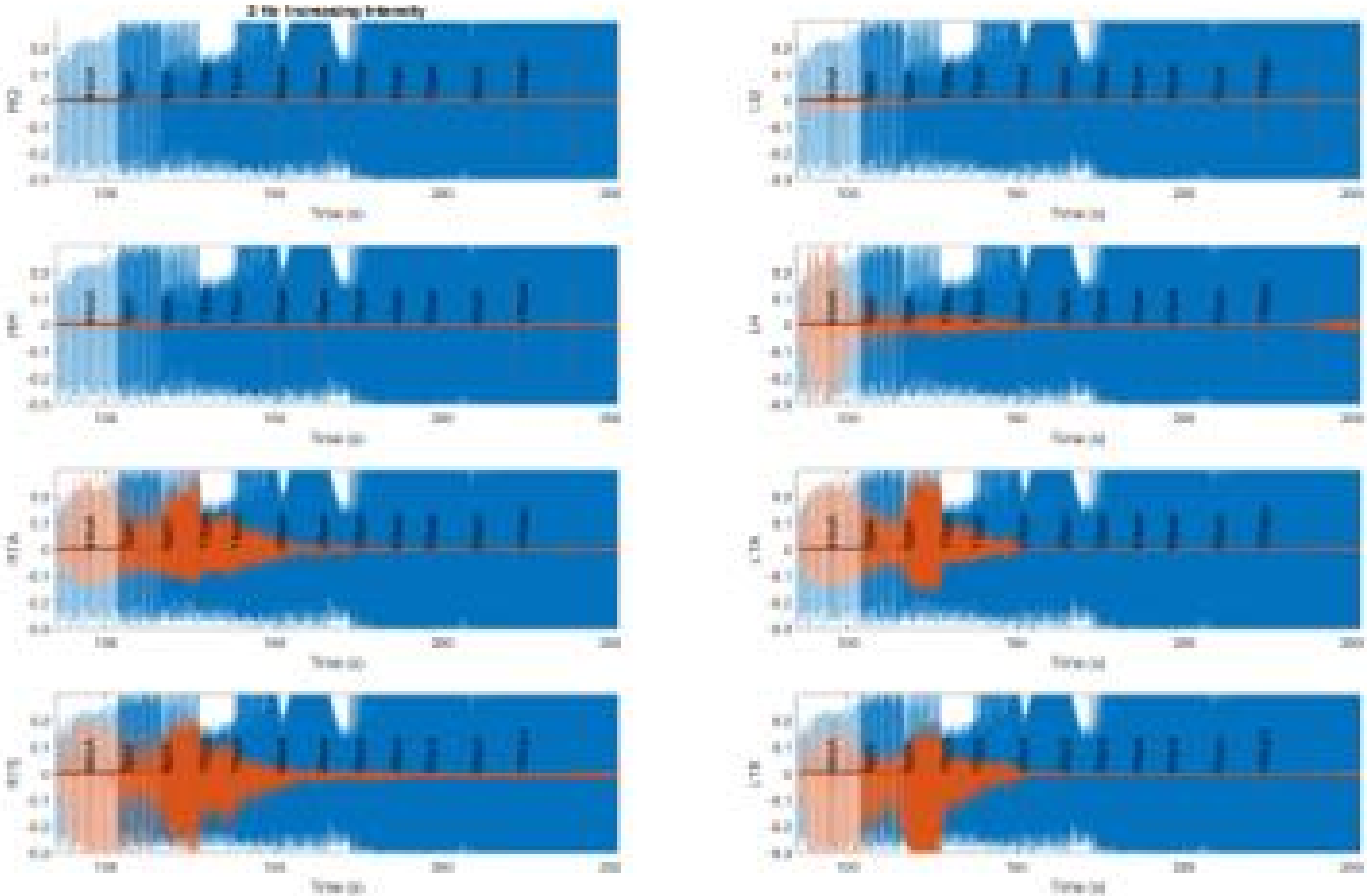


10V , 16Hz



P21VF Session 2019-11-11

Frequency Sweep at 40mA
(Blue: Stimulation, Orange: EMG)



LS11-057

Augmentation of residual neural control by non-invasive spinal cord stimulation to modify spasticity in spinal cord injured people

Main results and impact

Babinski

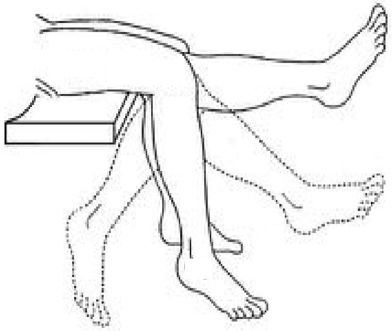
NO stimulation

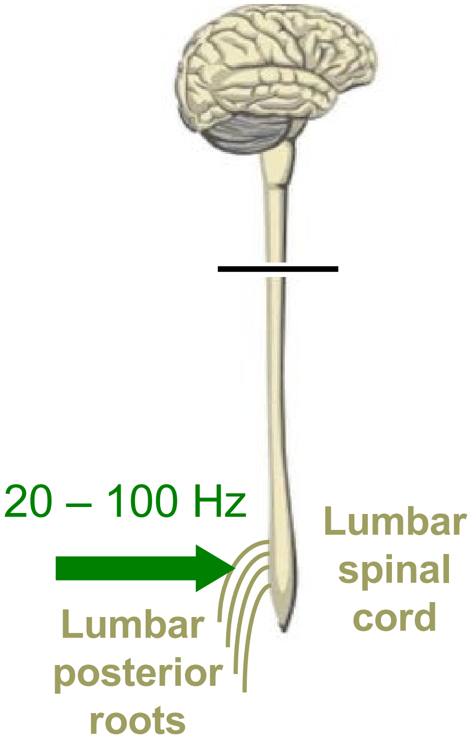
10pps / 20mA

50pps / 40mA

Control of spasticity

Assessment of spasticity using the Pendulum test



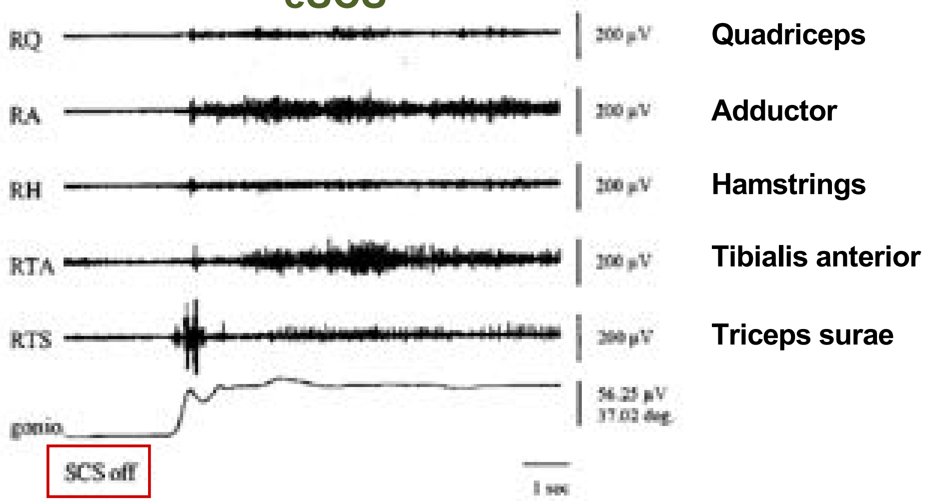


Pinter et al. (2000) Spinal Cord

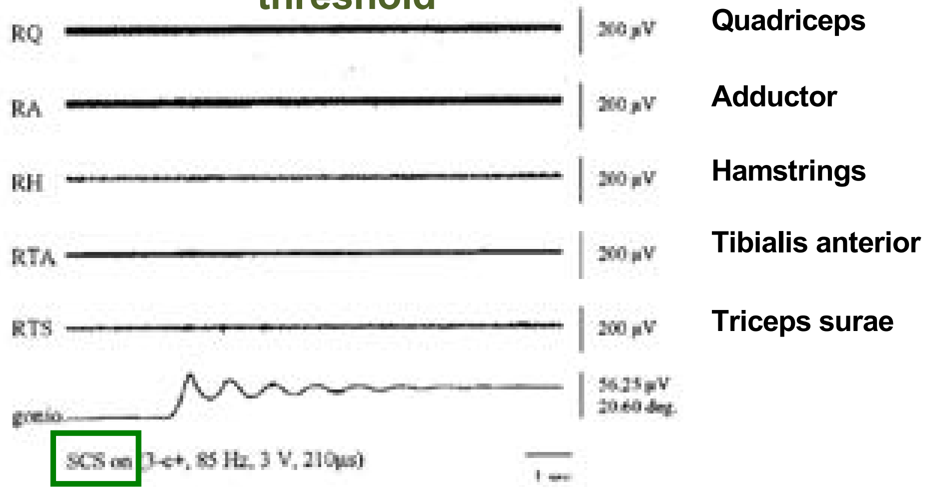
8 Subjects
7 motor complete,
1 ASIA C

Traumatic SCI
C5 to T6

without eSCS

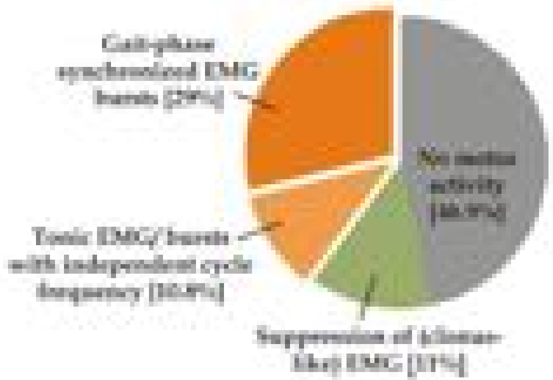


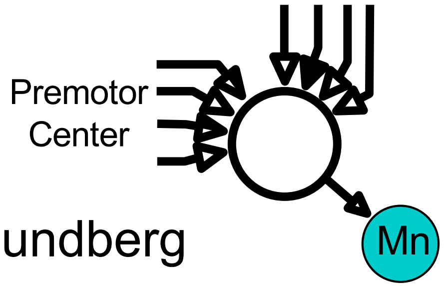
with eSCS – 85pps, submotoric threshold



Shepherd Center

effect groups:

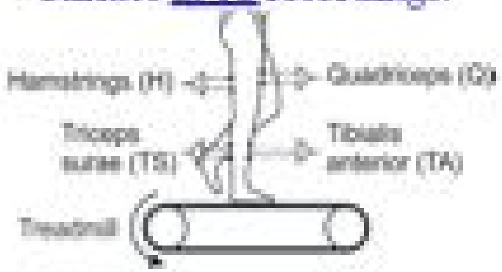


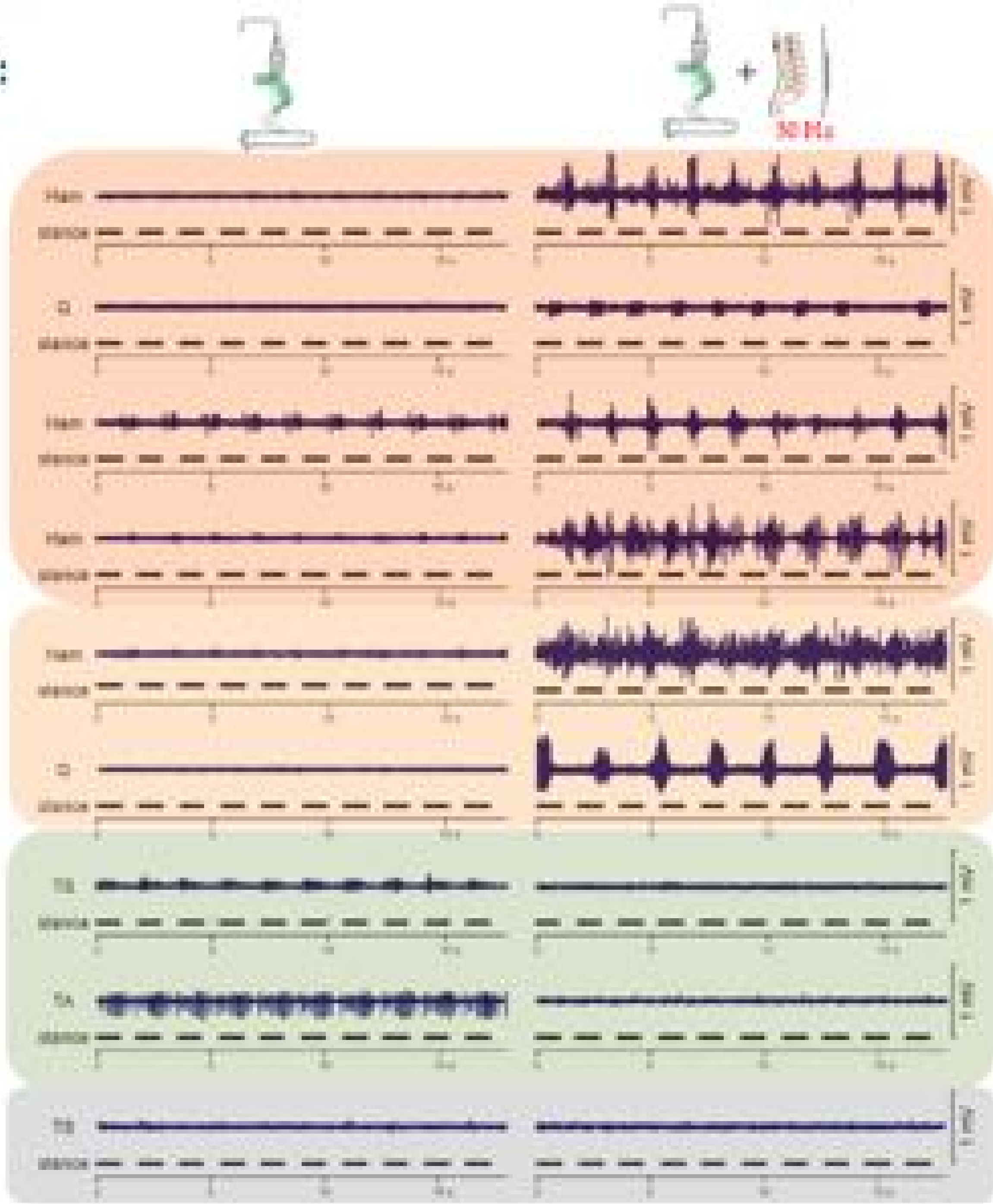


1979

Anders Lundberg

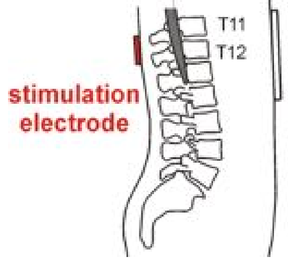
Surface EMG recordings:

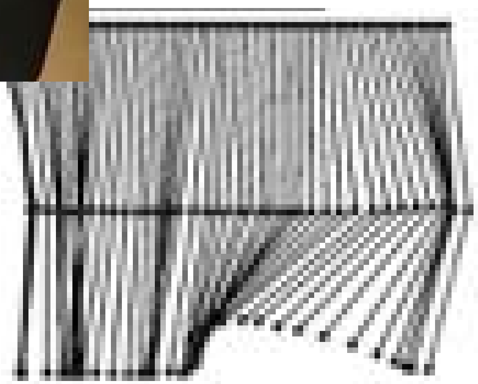




Facilitation of stepping in incomplete SCI by tSCS

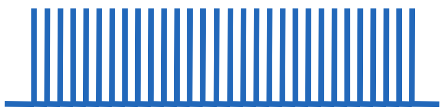
Subject:
ASIA D, T8-T9

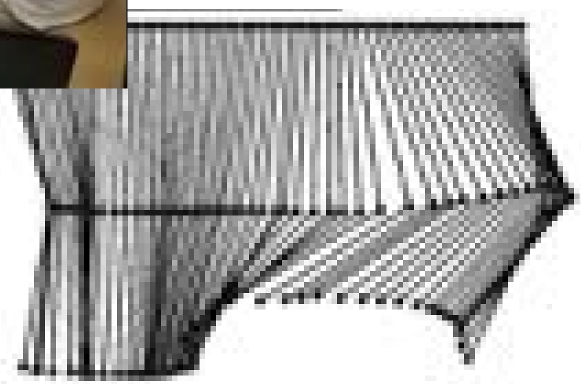




1.6 km/h; no stimulation

1.6 km/h
tSCS: 30 Hz, 18 V





Facilitation of functional standing and walking in wheel-chair bound spinal cord injured people by spinal cord stimulation: Study of neurocontrol and biomechanical output
WFL-FR-001/06

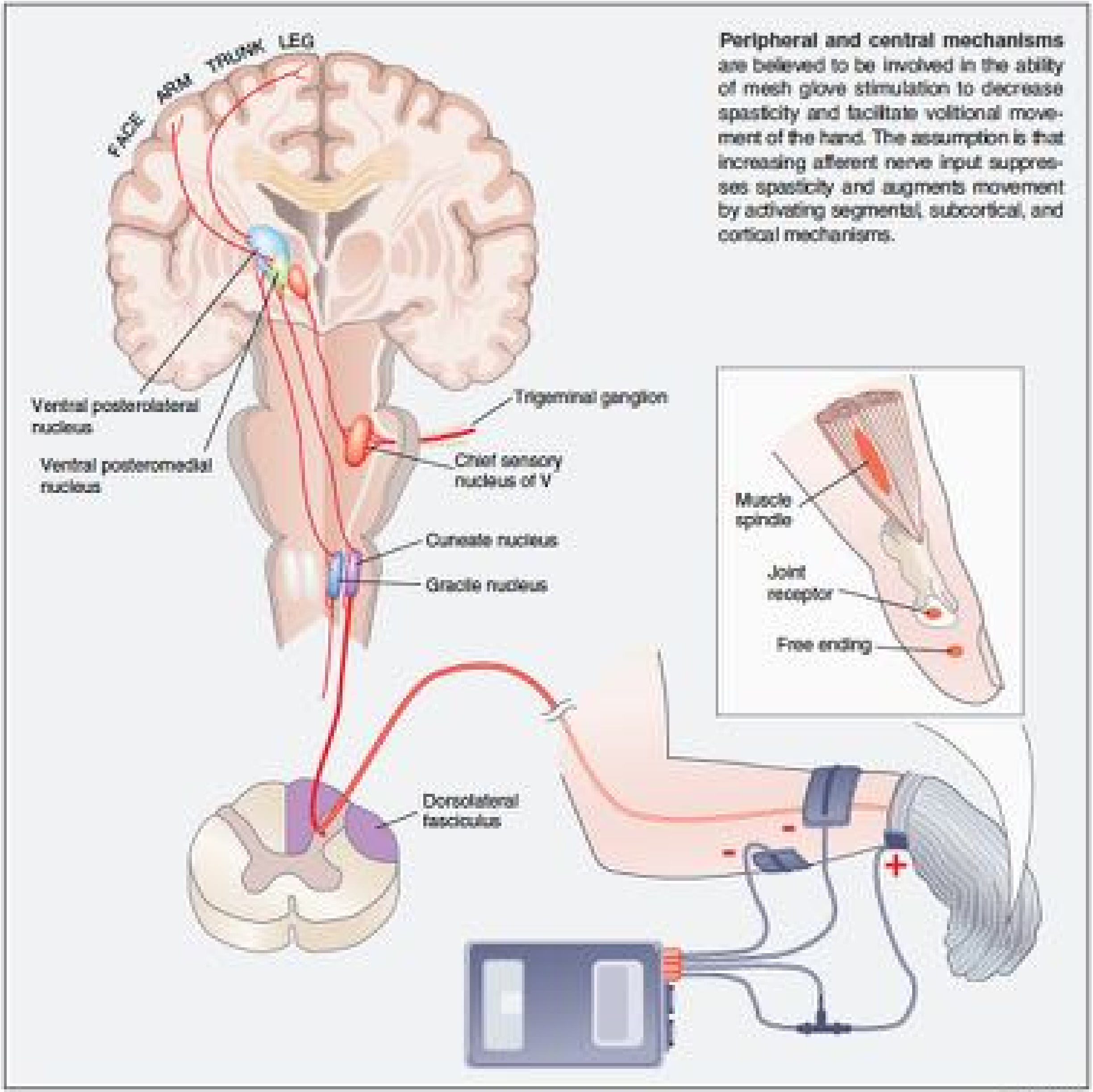
Dimitrijevic MR
Clinical practice of FES: From "Yesterday" to "Today"
Artificial Organs. 2008 Aug;32(8):577-80

Mesh Glove Electrical Stimulation

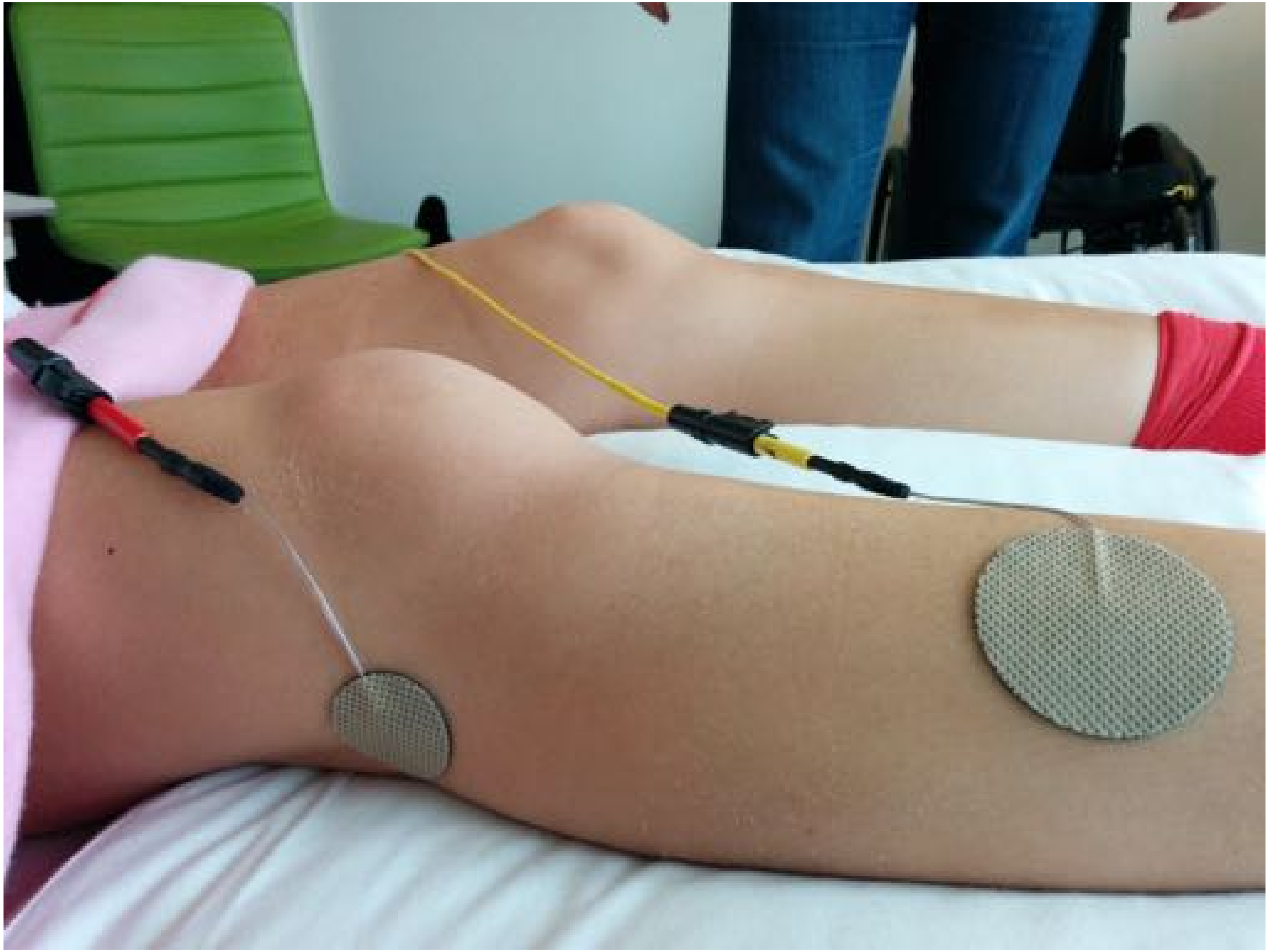
by M. Meta Dimitrijević, Nachum Soroker, and Fabian E. Pollo

SCIENCE & MEDICINE

May/June 1996



Peripheral and central mechanisms are believed to be involved in the ability of mesh glove stimulation to decrease spasticity and facilitate volitional movement of the hand. The assumption is that increasing afferent nerve input suppresses spasticity and augments movement by activating segmental, subcortical, and cortical mechanisms.



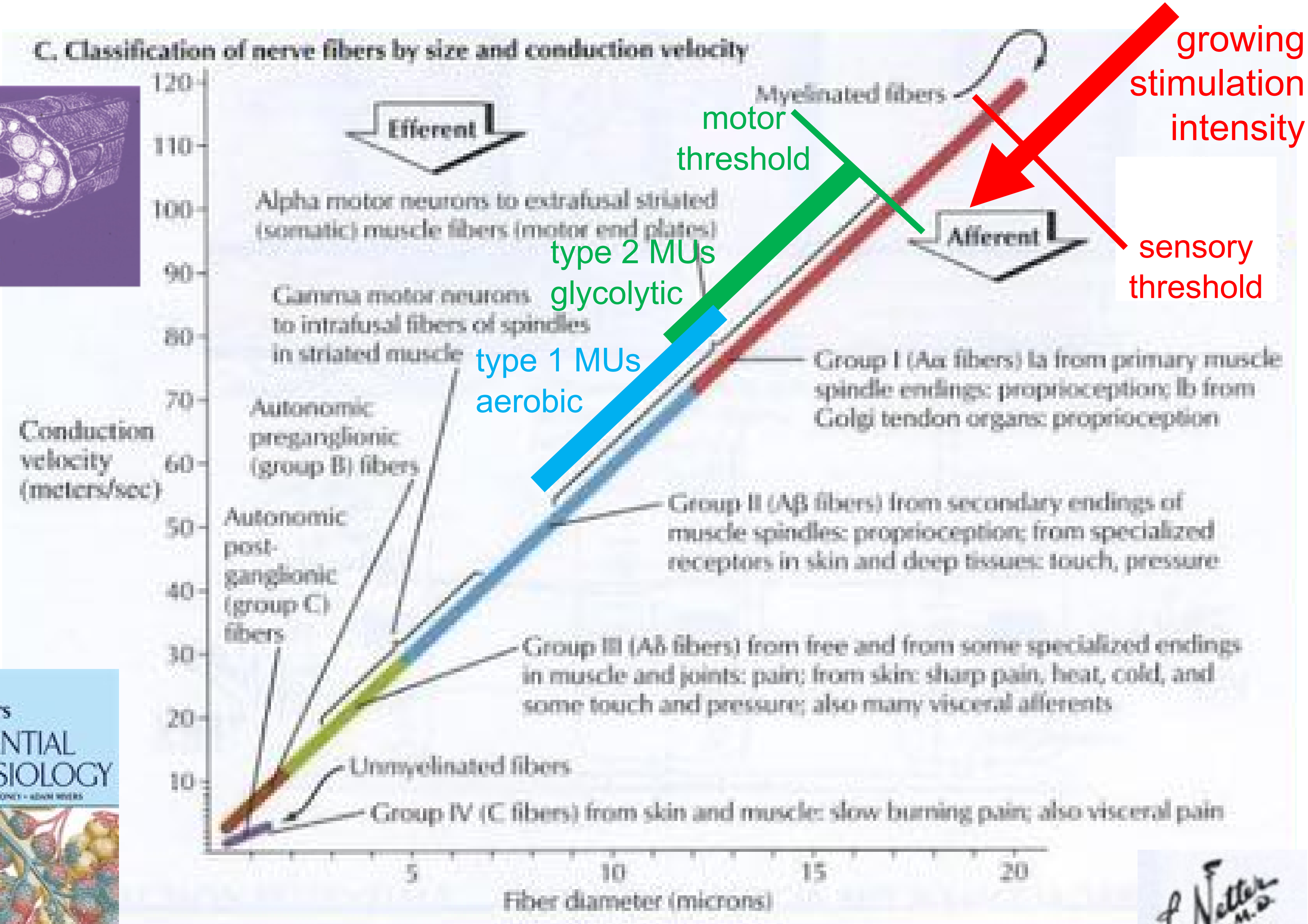
Peroneal Nerve

subsensory continuous: 1a afferents - supra-motor-threshold: withdrawal

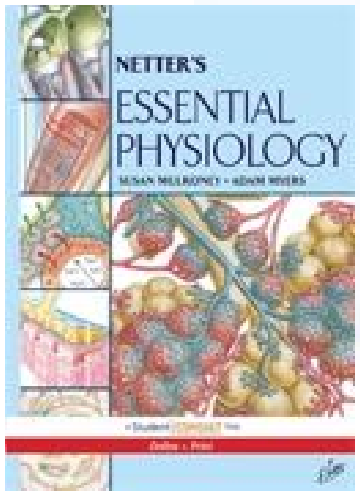
EXOPULSE Mollii Suit
Stockholm, Sweden

EXOPULSE

ottobock.



C. Classification of nerve fibers by size and conduction velocity
Conduction velocity (meters/sec)
120
110
100
90
80
70
60
50
40
30
20
10
Fiber diameter (microns)
5
10
15
20
Efferent
Afferent
Myelinated fibers
Unmyelinated fibers
Alpha motor neurons to extrafusal striated (somatic) muscle fibers (motor end plates)
Gamma motor neurons to intrafusal fibers of spindles in striated muscle
Autonomic preganglionic (group B) fibers
Autonomic post-ganglionic (group C) fibers
Group I (Aα fibers) Ia from primary muscle spindle endings: proprioception; Ib from Golgi tendon organs: proprioception
Group II (Aβ fibers) from secondary endings of muscle spindles: proprioception; from specialized receptors in skin and deep tissues: touch, pressure
Group III (Aδ fibers) from free and from some specialized endings in muscle and joints: pain; from skin: sharp pain, heat, cold, and some touch and pressure; also many visceral afferents
Group IV (C fibers) from skin and muscle: slow burning pain; also visceral pain
growing stimulation intensity
motor threshold
sensory threshold
type 2 MUs glycolytic
type 1 MUs aerobic



NETTER'S
ESSENTIAL PHYSIOLOGY

SELECTIVITY

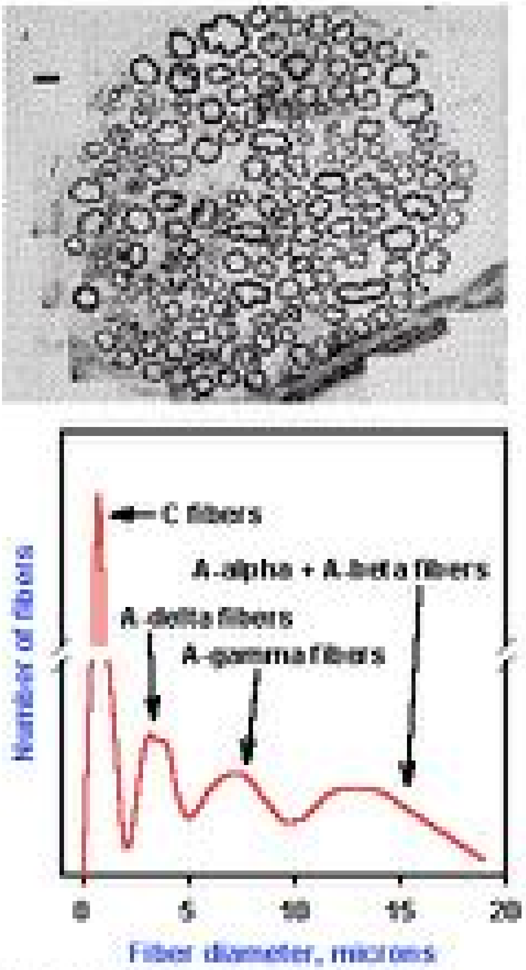
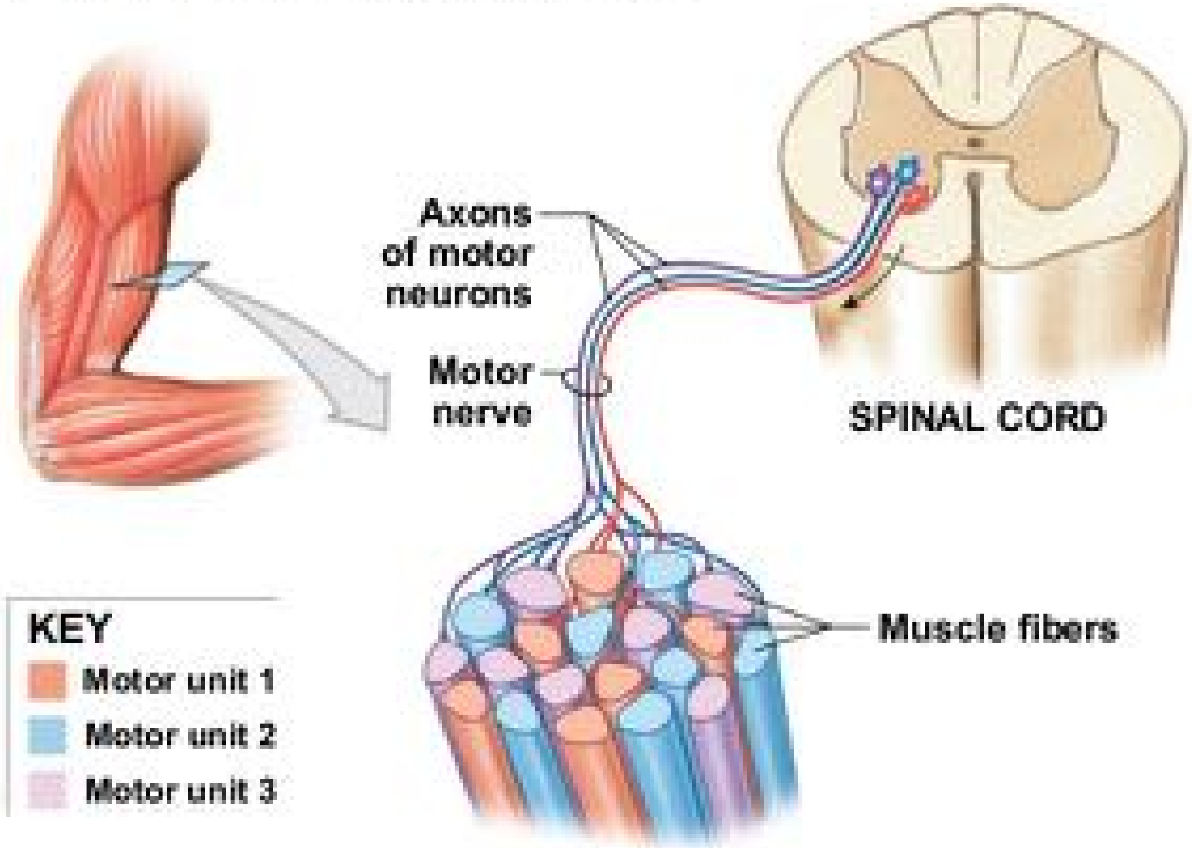


Fig. 5-13. Distribution of fibers within a peripheral nerve. Upper: A cross section of the posterior articular nerve of the cat showing fibers of different diameters. Calibration: 10 microns (Courtesy of F.J. Clark). Lower: A plot of the number of fibers of different diameters in a peripheral nerve. Note the predominance of fibers less than 2 microns in diameter.

Figure 9.12 The Arrangement of Motor Units in a Skeletal Muscle

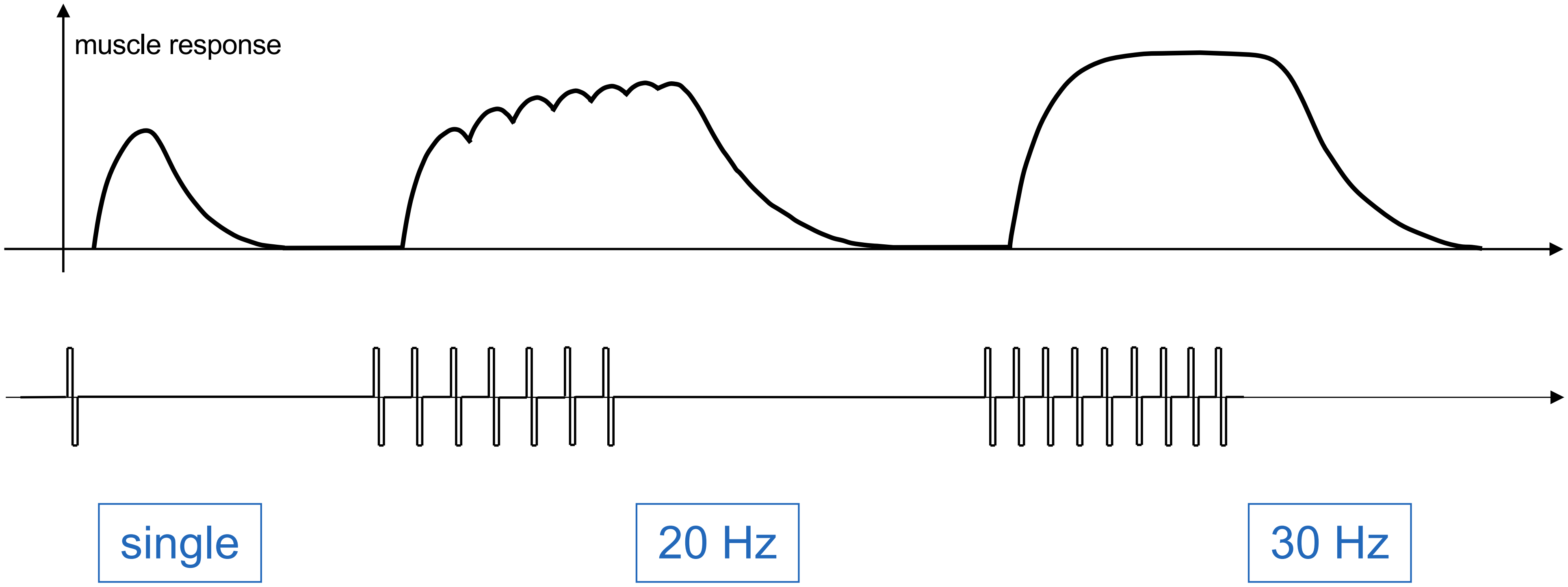


Michael D. Mann:
The Nervous System in Action
http://michaeldmann.net

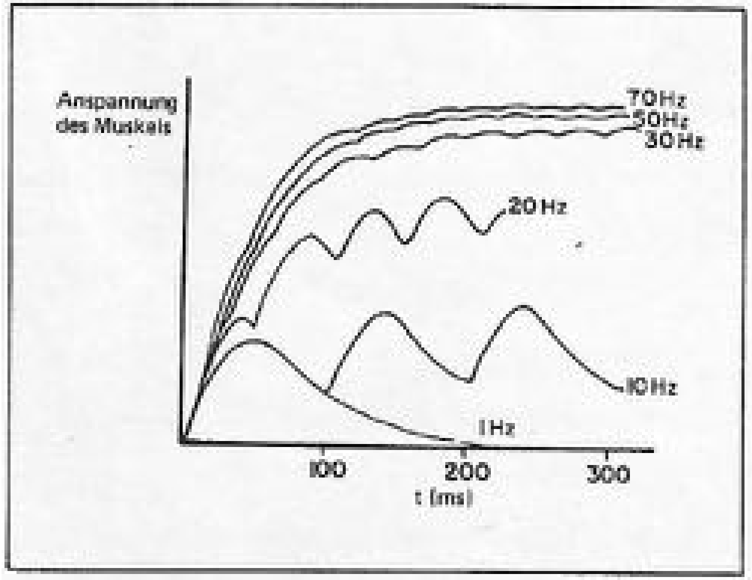
MIXED NERVE, predominantly afferent

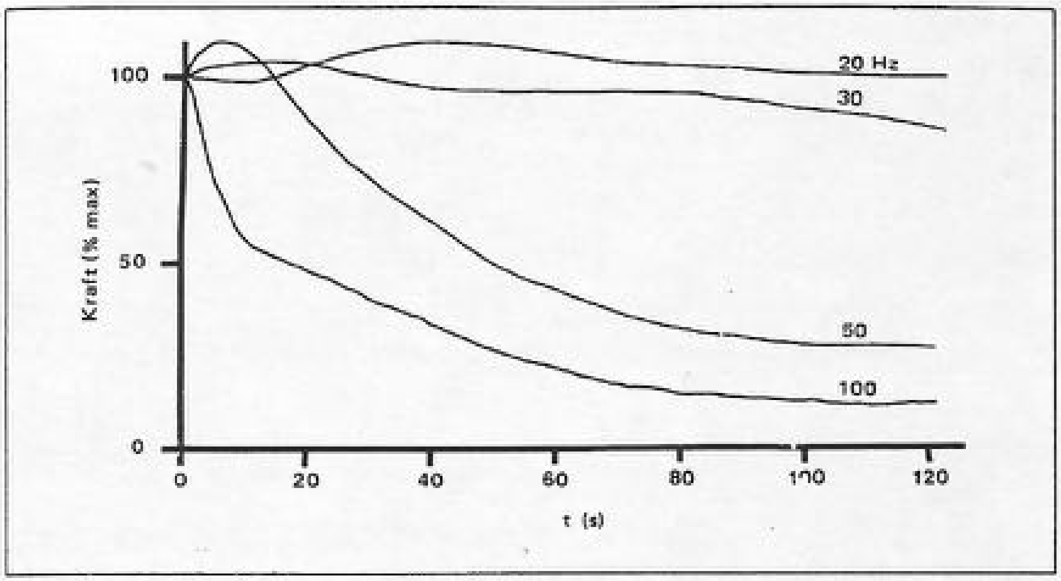
Glycolytic & aerobic motor units –
- mixed morphology in nerve and muscle

Control-, metabolic and biomechanical issues

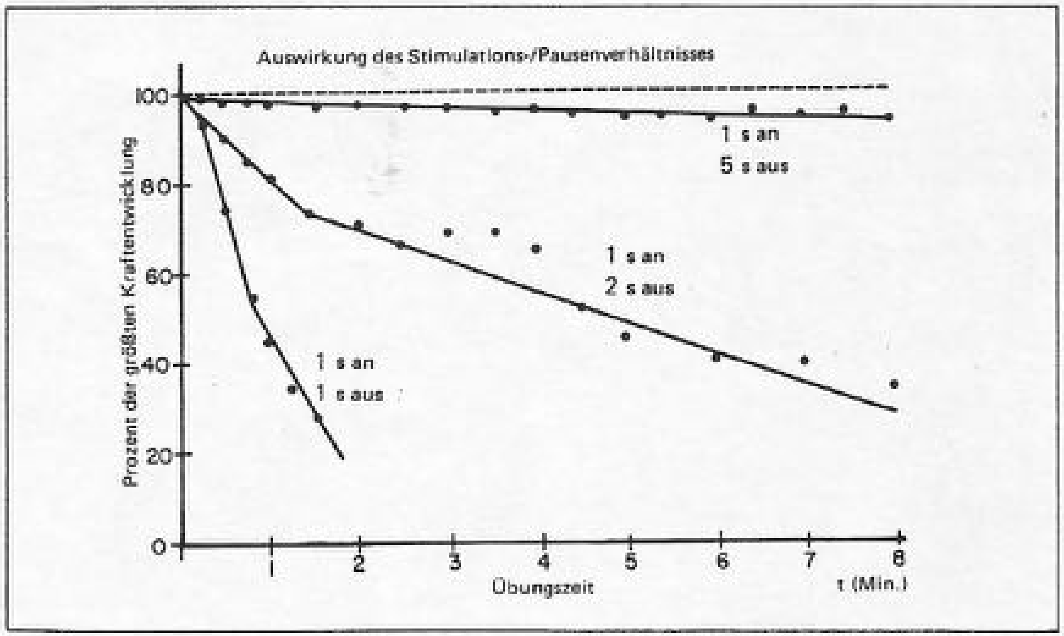

muscle response
single
20 Hz
30 Hz

Frequency dependence of contraction force development and muscle fatigue



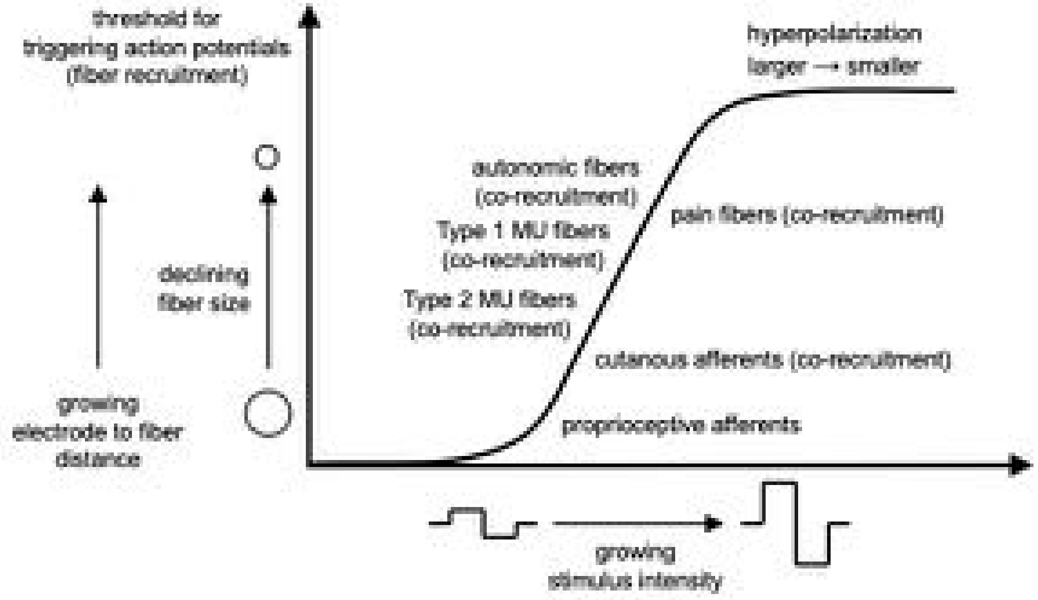


ON-/OFF-relation dependence of muscle fatigue



Summary

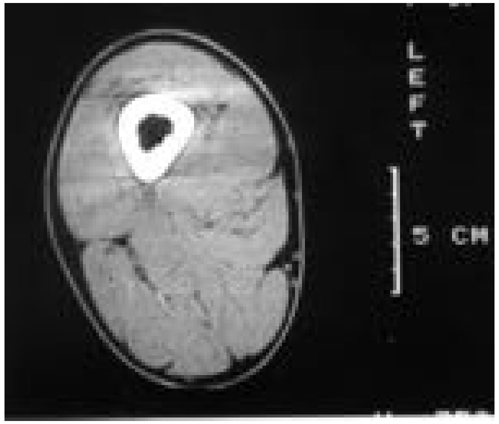
Stimulation interface – neuron activation



- Size and distance dependent recruitment of fibers (in groups)
  - Lowest threshold – large afferents
  - Growing intensity co-recruits smaller fibers gradually
- Synchronous start – dispersion by distance and conduction velocity
- Beyond recruitment - frequency influences
  - central interneuron processing as afferent input
  - contraction properties in efferent neuromuscular activation

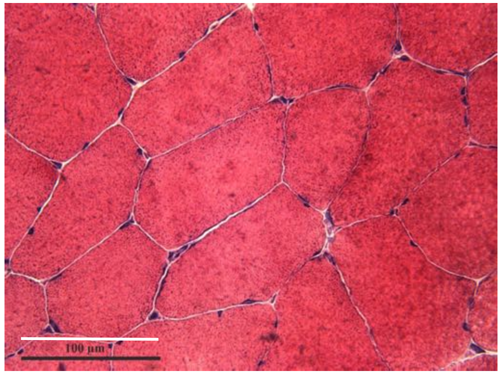
Consequences of muscle denervation

Healthy thigh

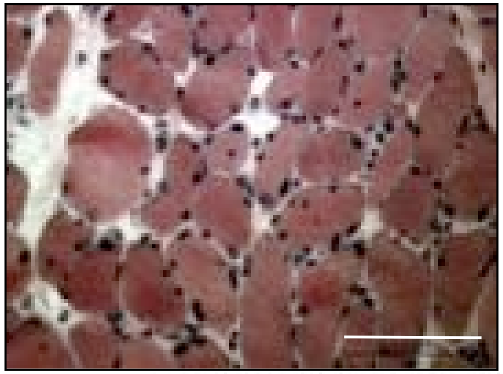


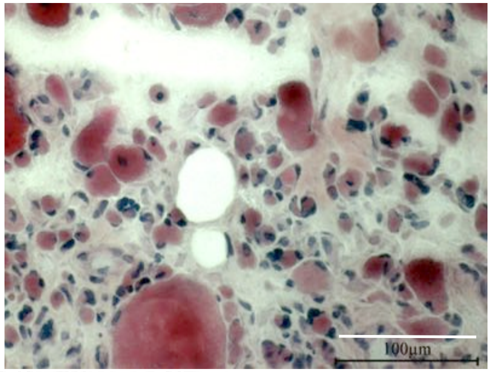
4 years denervated

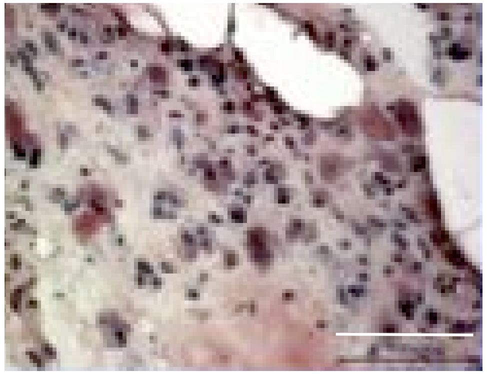
8,7 years denerv.

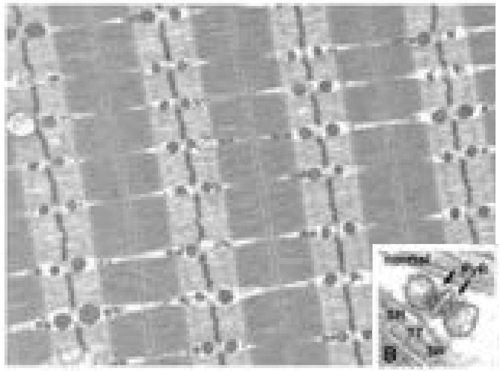


0,9y den

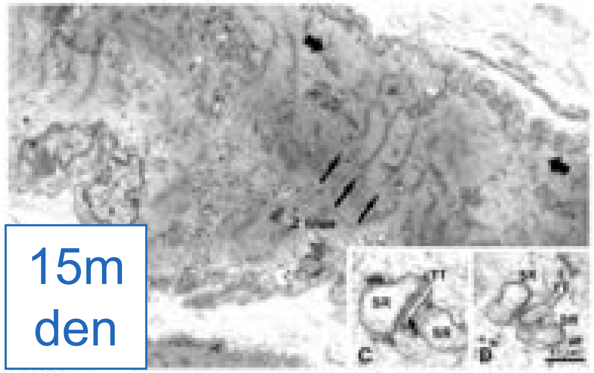








15m den



MFCV$_{max}$ vastus lat:	
healthy	4,48 m/s
10mo den	2,40 m/s
30mo den	1,20 m/s

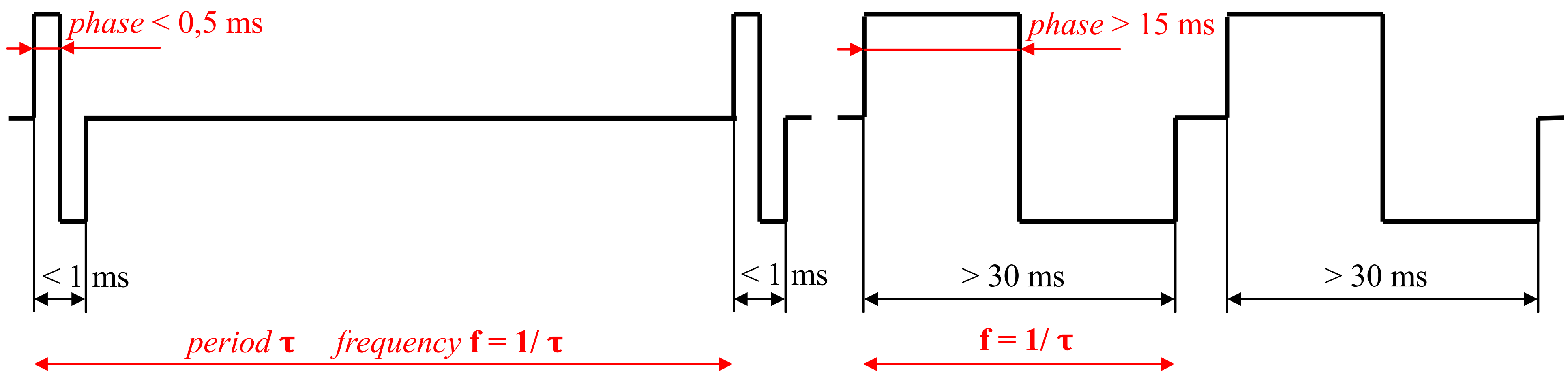
Stimulation parameter ranges

Nerve stimulation:

- Pulse width (biphasic)
  typ. < 0.5ms per phase
- Frequency (fused contr.)
  25 Hz
- Amplitude range (Surface)
  ⇨ ±100V / ⇨ ±300mA
- Amplitude range (Implant)
  ⇨ ±10V / ⇨ ±30mA

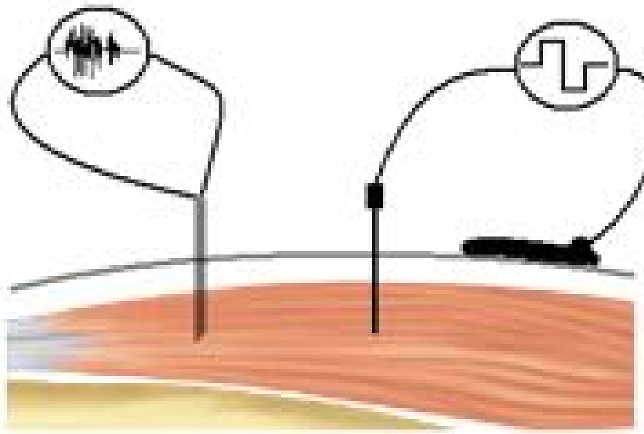
Muscle stimulation:

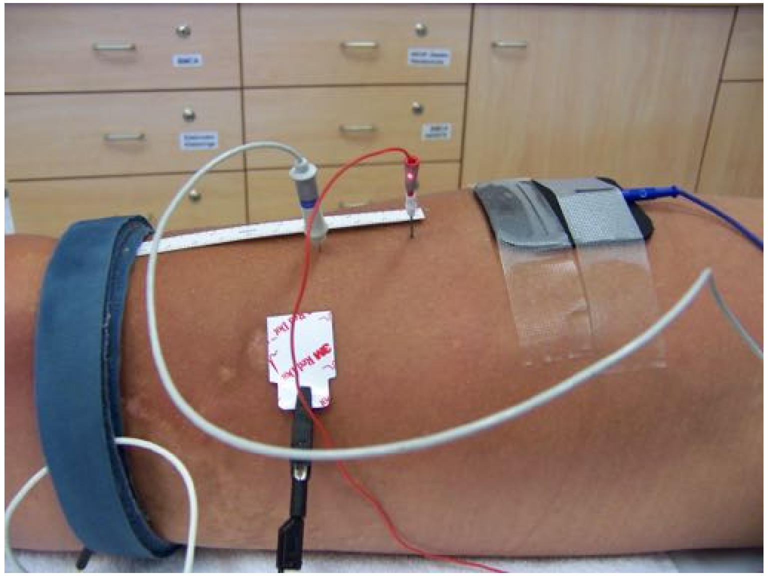
- Pulse width (biphasic)
  typ. >15ms (⇨250ms) per phase
- Frequency (fused contr.)
  25 Hz
- Amplitude range (Surface)
  ⇨ ±100V / ⇨ ±300mA
- Amplitude range (Implant)
  ⇨ ±10V / ⇨ ±30mA



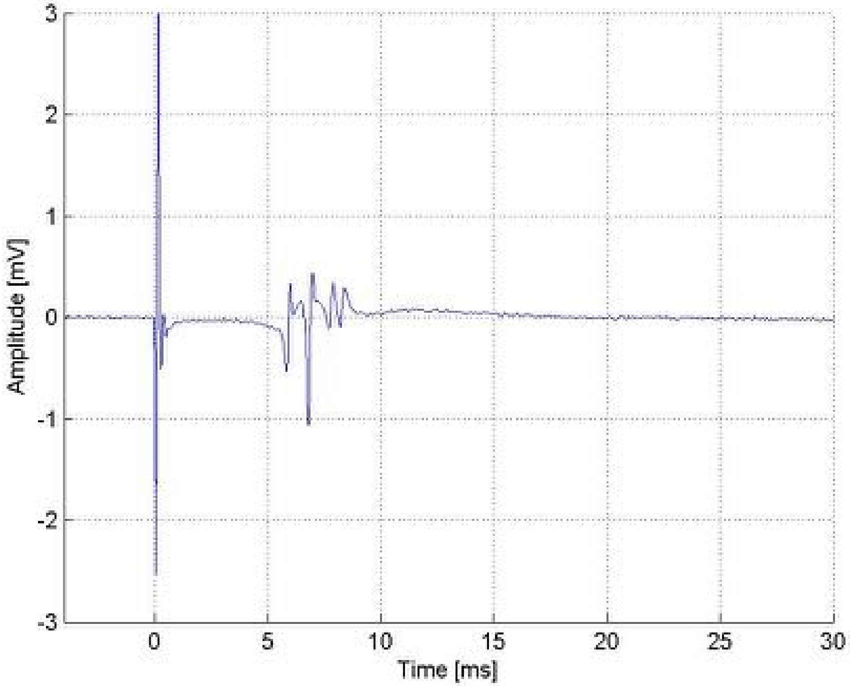
Single fiber recording

(PhD-Thesis Christian Hofer 2008)

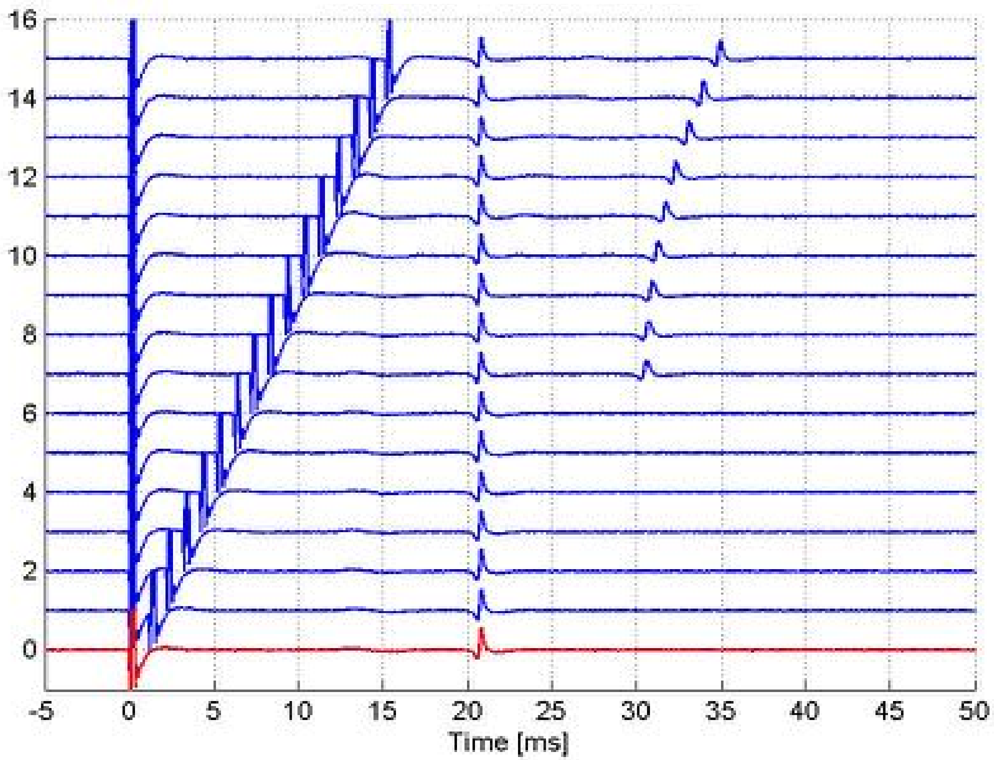


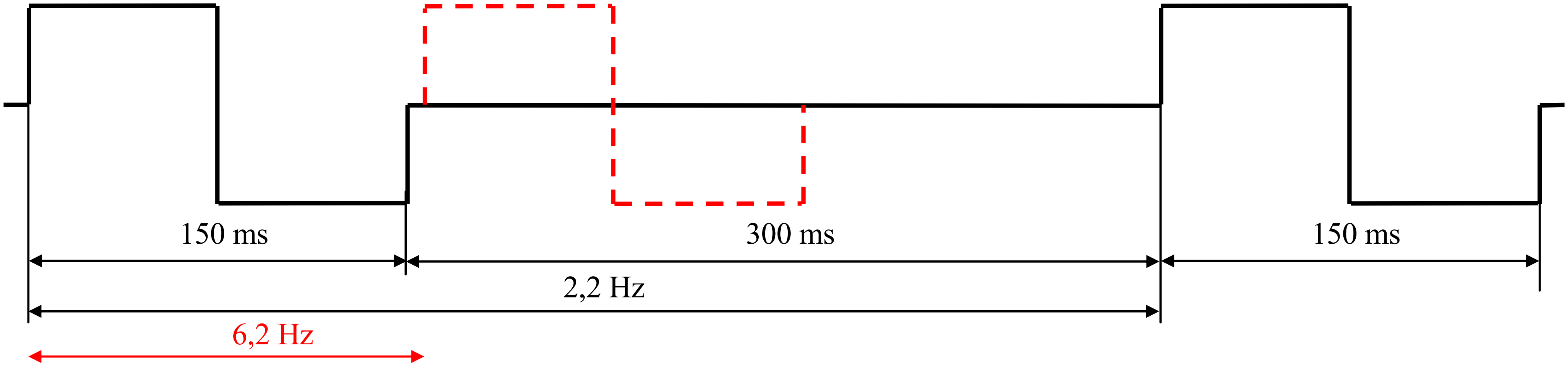


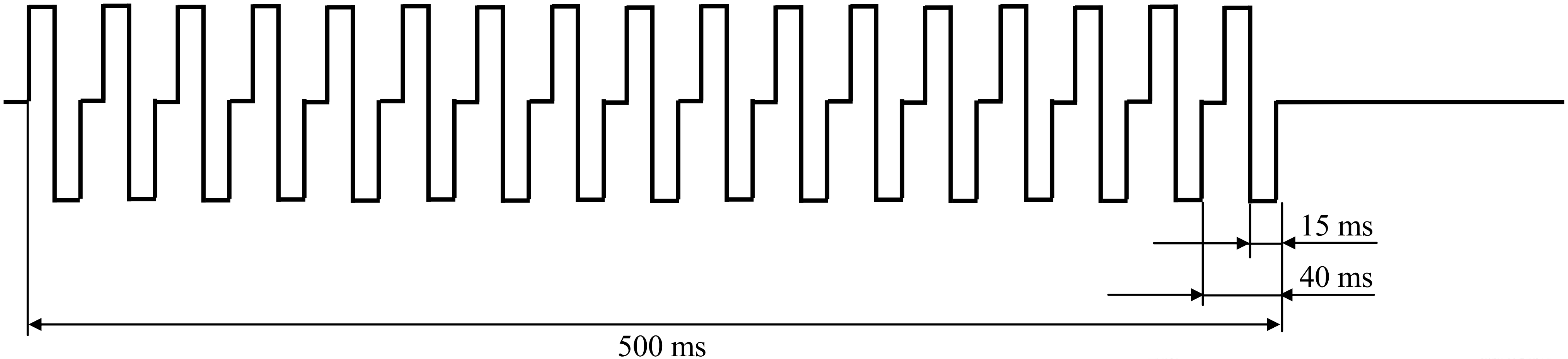
Single stimulus response



Double stimulus response

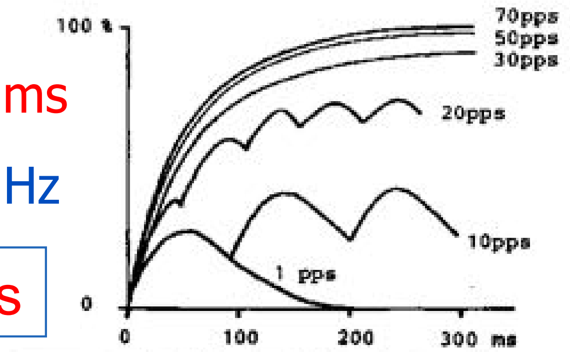




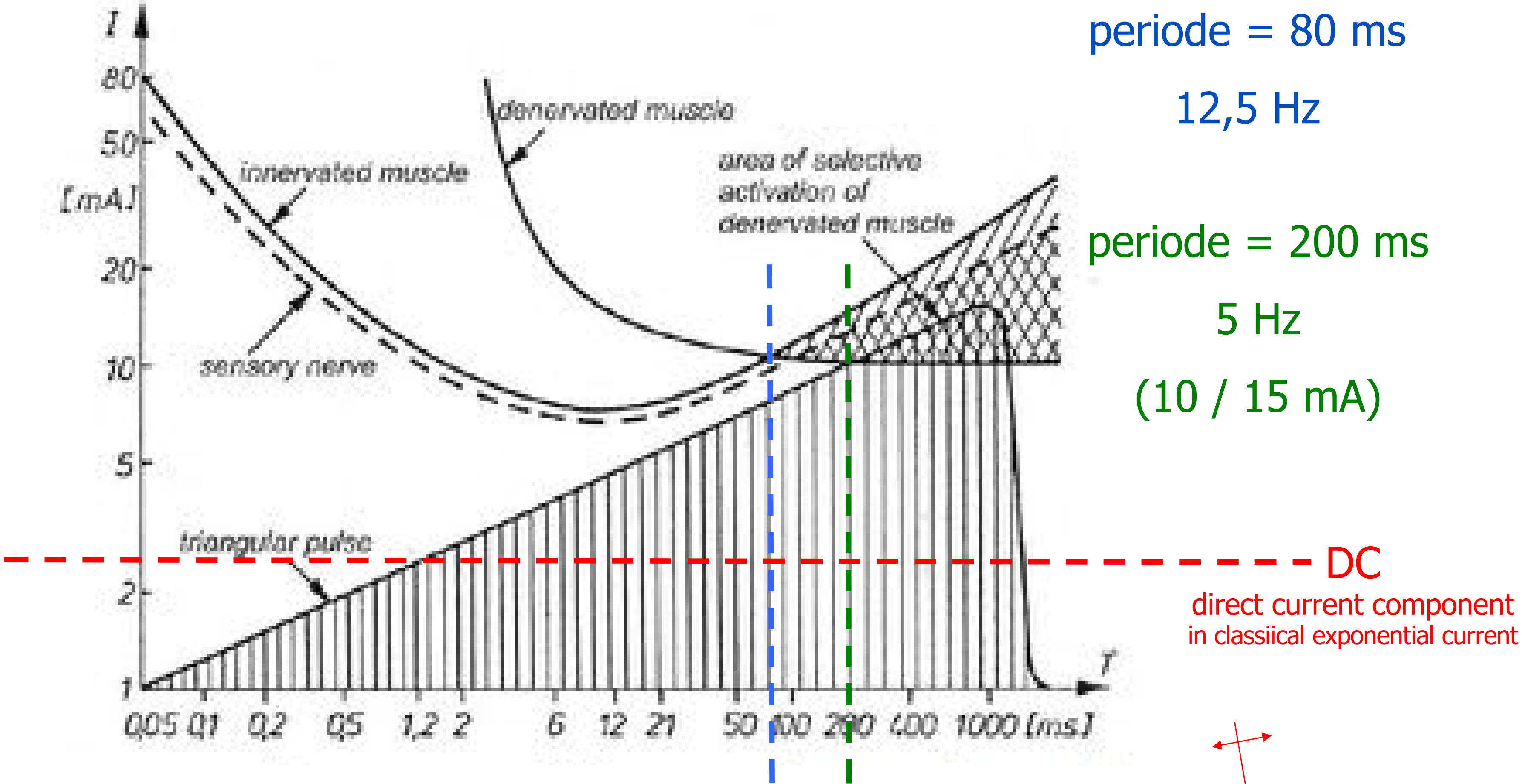


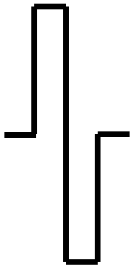
Excitability | Period < 50 ms | Pulse phase > 15 ms

conditioning | > 20 Hz | Period 40ms / 25 Hz

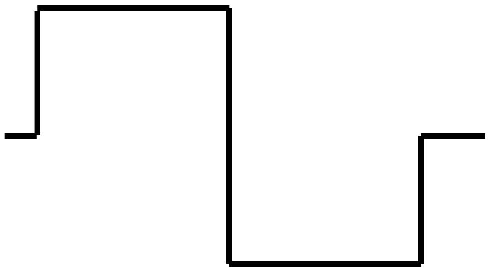


Single twitch ⇨ unfused tetanus ⇨ fused tetanus

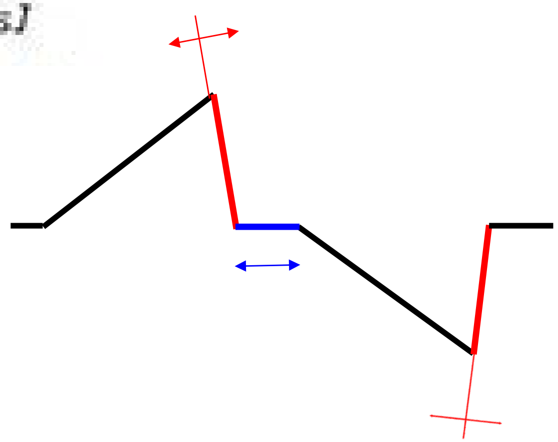




nerve stimulation



muscle stimulation



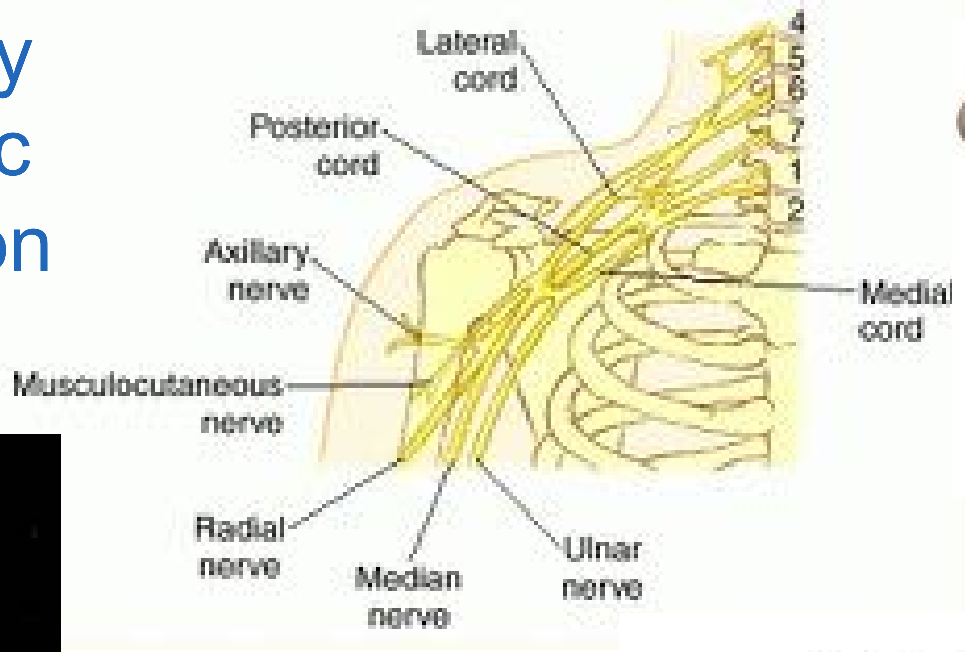
muscle stimulation,
reduced nerve stimulation

sub C5/C6, AIS A
5 years post injury
2x / week, 20min:
Single twitch FES, low frequency, 80ms per phase and pause

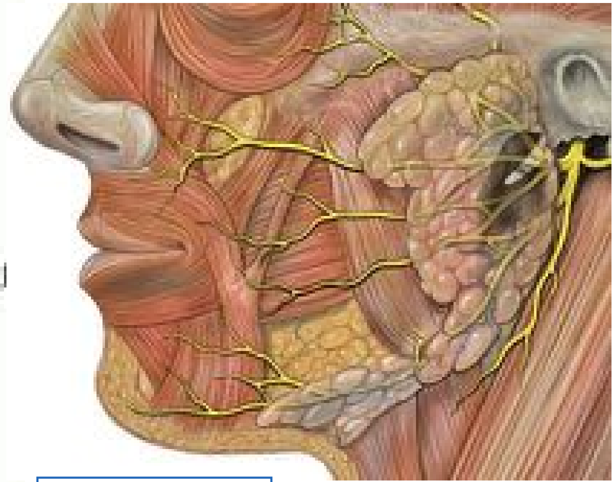
biphasic rectangular
30 Hz, 1ms/phase

biphasic ramp
150ms/phase
150ms pause

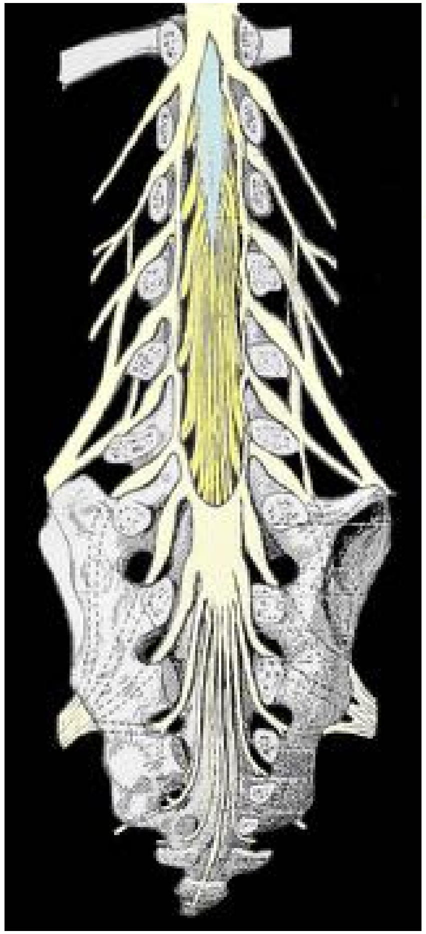
Temporary or chronic denervation



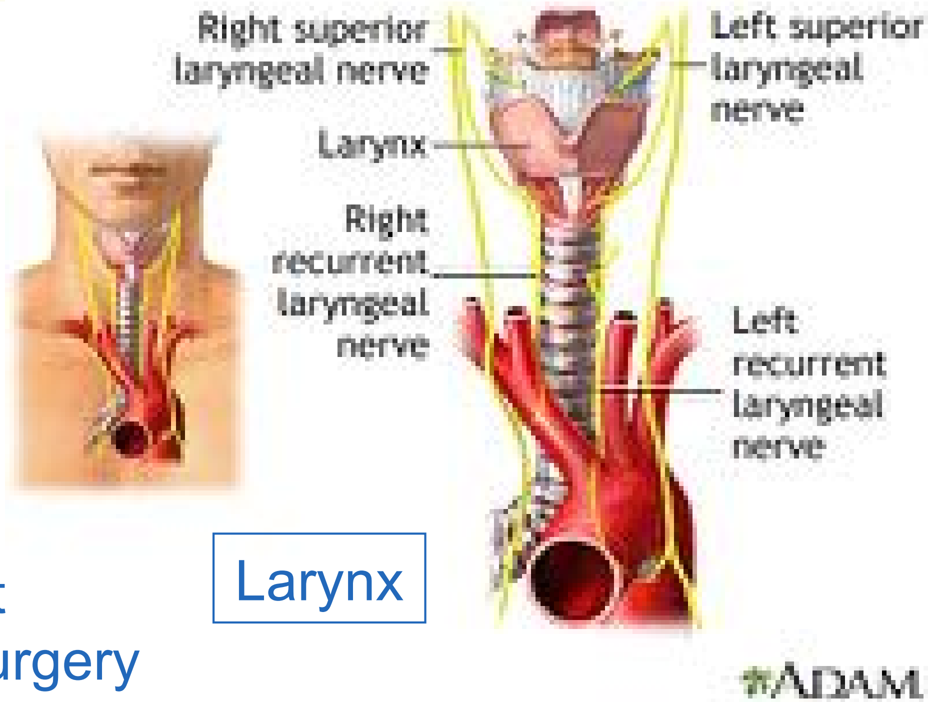
Plexus



Facialis



Cauda



Larynx

Recovery support
Reconstructive surgery

implant

ASIA IMPAIRMENT SCALE

A – Complete: No motor or sensory function preserved in the sacral segments S4-S5.

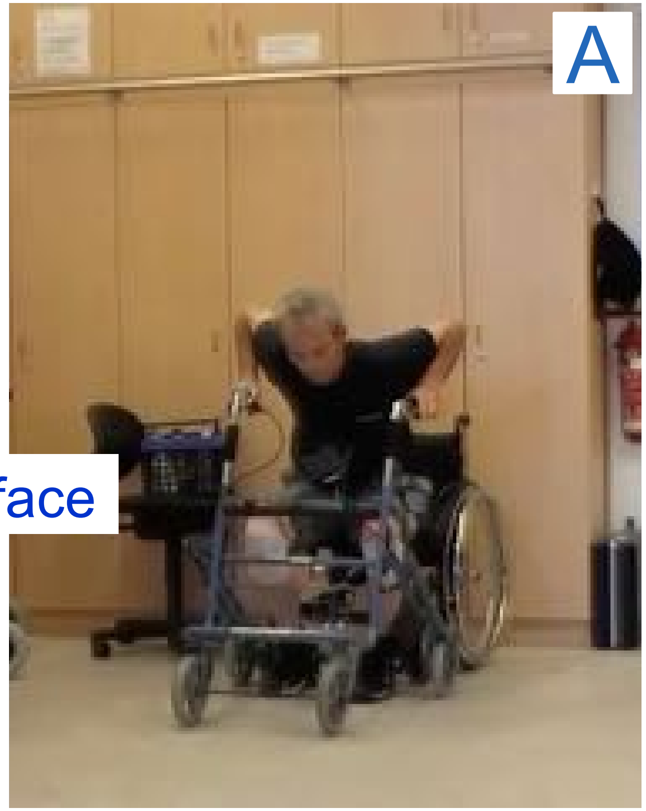
B – Incomplete: Sensory but not motor function preserved below neurological level and includes the sacral segments S4-S5.

C – Incomplete: Motor function preserved below neurological level, and more than half of key muscles below the neurological level have muscle grade below 3.

D – Incomplete: Motor function preserved below neurological level, and more than half of key muscles below the neurological level have muscle grade of 3 or more.

E – Normal: Motor and sensory function normal

surface



Paraplegia

Herrn JALLABERT,

Professors der Experimental-Philosophie und Mathematick, Mitglieds der Königl. Gesellschaften der Wissenschaften zu London und Montpellier, wie auch der Akademie des Instituti Bononiens.

EXPERIMENTA
ELECTRICA
USIBUS MEDICIS APPLICATA.
Oder

Versuche

über die

Electricität,

aus denen der herrliche Nutzen derselben in der

Artzneywissenschaft

und insbesondere in der Kur eines Lahmen zu ersehen,

nebst einigen Muthmassungen über die Ursach der Wirkungen der Electricität.

Denen zu Ende beygefügt

Herrn de SAUVAGES
Königl. Raths und Professors zu Montpellier &c.

Sendschreiben,
an Herrn D. BRUHIER,
von den Versuchen so an einigen Lahmen unter seiner Aufsicht gemacht worden.

Aus dem Französischen übersetzt.

BASEL, bey Johann Rudolf Im Hof,
1750.

Nachricht

des Herausgebers der Pariser Ausgabe.

von Montpellier erhalten, hier beyfüge. Es scheinet derselbe sehr tauglich zu seyn, zu Anstellung neuer Versuchen aufzumuntern, und man kan hoffen, daß die Electricität für Krankheiten die die Arzneywissenschaft bißher nur mit sehr ohnmächtigen Waffen angriffe, ein sehr kräftiges Mittel werden könne.

https://fesworkshop.org/14th-workshop-2022

Smile and Breathe: Atmung, Schlucken, Mimik – Chancen und Herausforderungen der Behandlung mittels Funktioneller Elektrostimulation

18. & 19. November 2022 im International FES Centre®, Nottwil und online via Zoom

Ziel des Kurses ist das Erlernen von theoretischen und praktischen Grundlagen der Behandlung mittels Funktioneller Elektrostimulation in der Neurorehabilitation bei Störungen der Atmung, des Schluckens und der Mimik.

https://www.paraplegie.ch/spz/de/kurs-atmung-schlucken-mimik-international-fes-centrer/