Functional connectivity in the human motor system

Tjeerd Boonstra

Faculty of Psychology and Neuroscience
Maastricht University

Neuroscience Research Australia

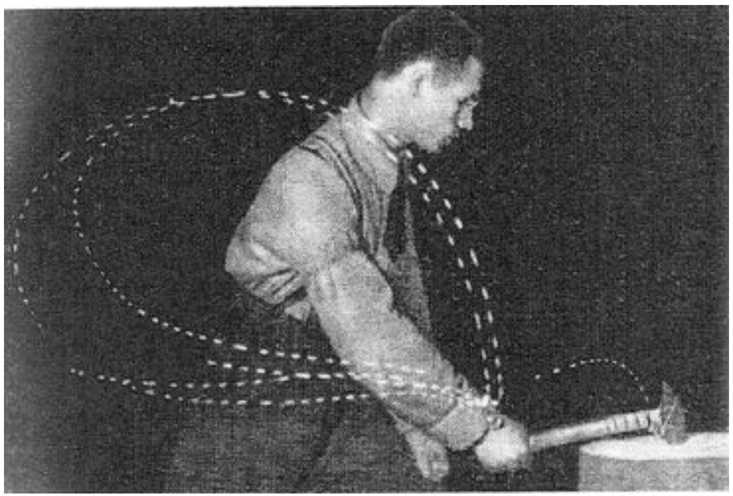
The human musculoskeletal system

~200 bones

~600 muscle

How does the central nervous system control this complex system?

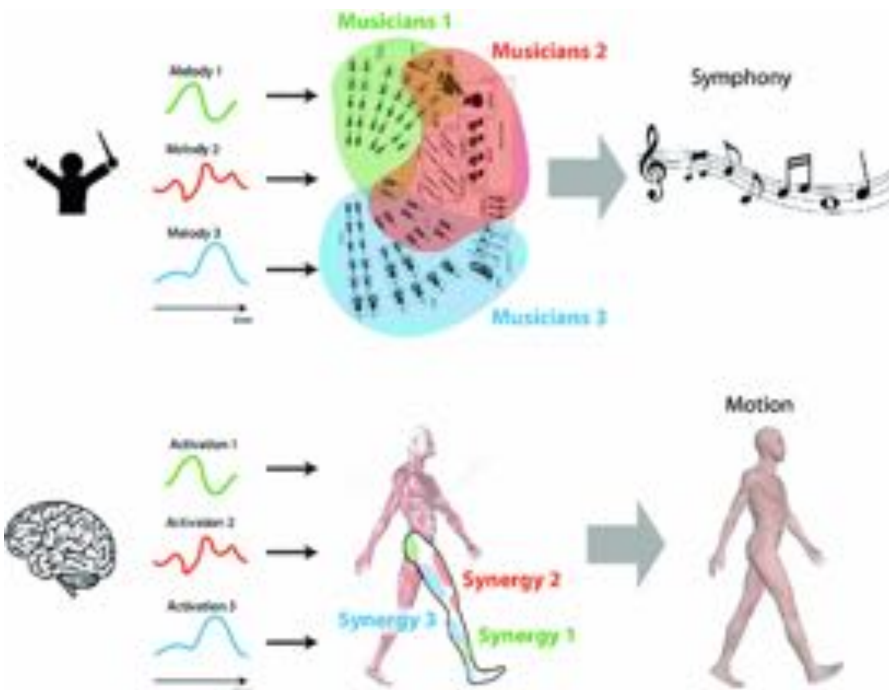
Human movement is low dimensional



Nikolai Bernstein (1896 – 1966)

Motor equivalence problem: Humans can perform a movement in multiple ways in order to achieve the same goal. **How does the nervous system chooses a solutions from this abundant set of possibilities?**

Human movement is low dimensional

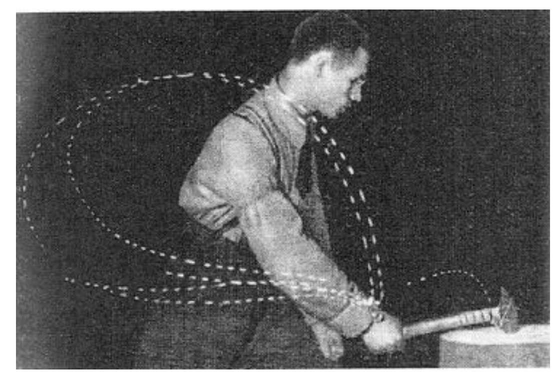


Movement are low dimensional and can be explained by a small number of factors

→ Activation patterns of different muscles (or movement patterns of different joints) are correlated

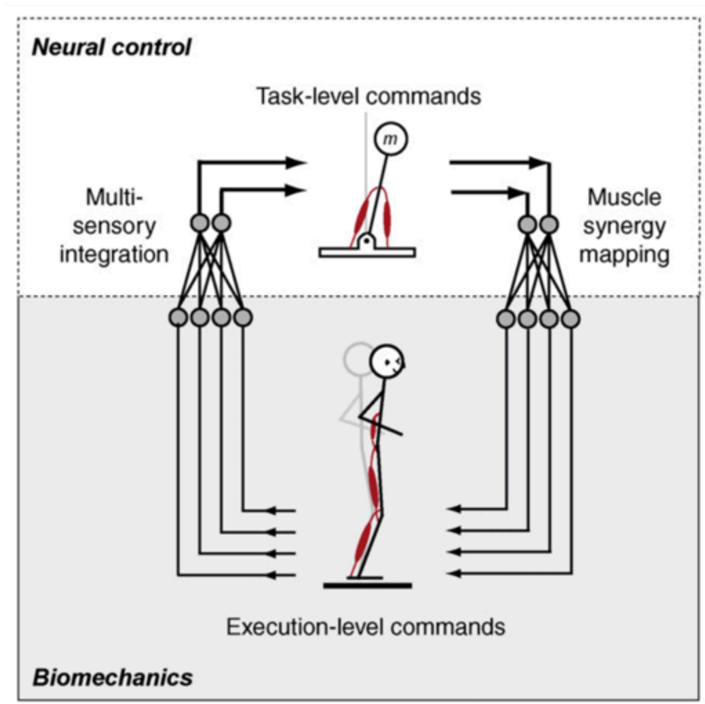
Controlling the musculoskeletal system

constraints imposed by nervous system



Constraints imposed by central nervous system

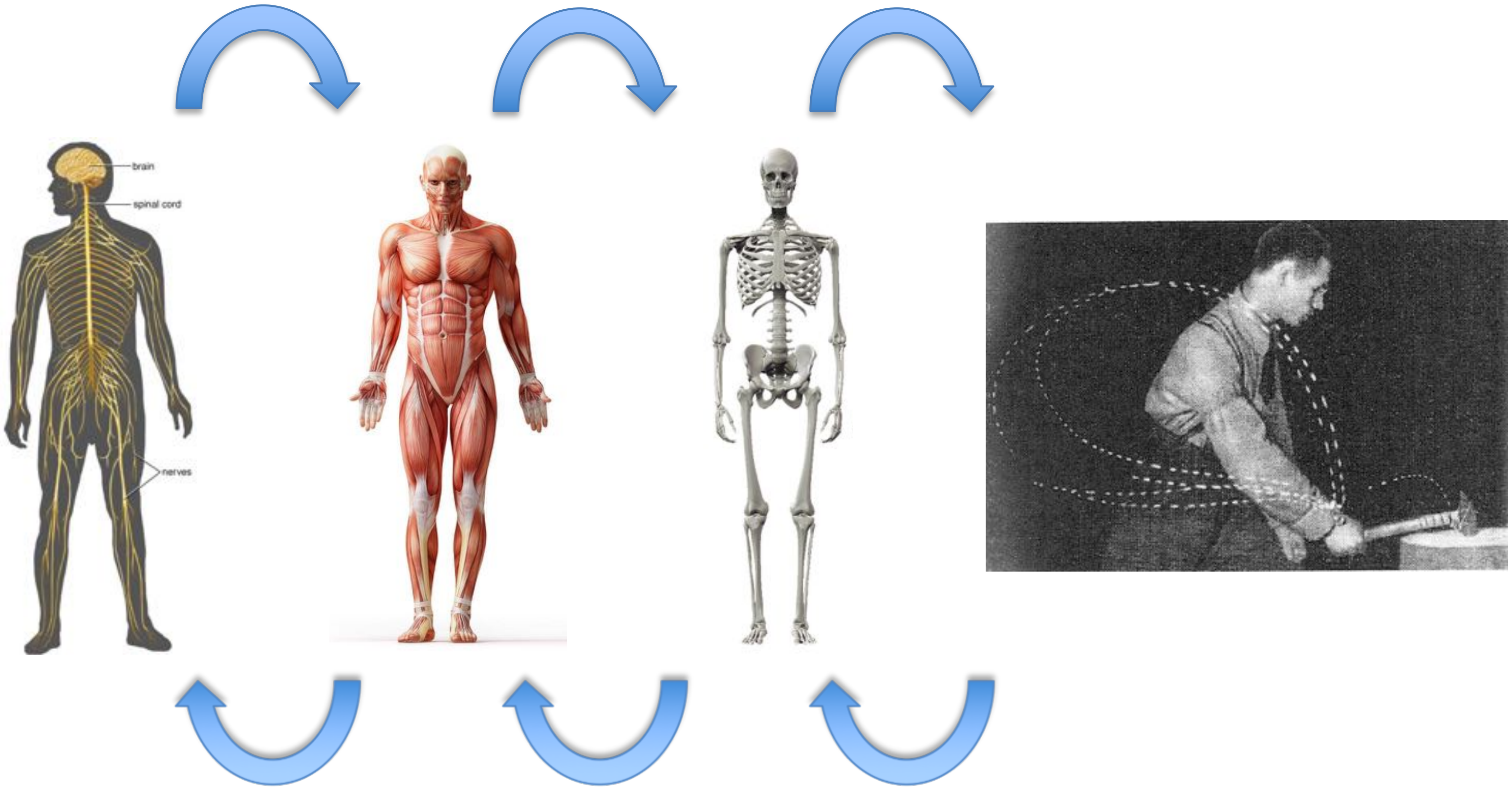
- Muscle synergies are building blocks that generate muscle activation patterns
- Muscle synergies may be implemented in spinal cord



Ting and McKay, 2007, *TINS 17*

Controlling the musculoskeletal system

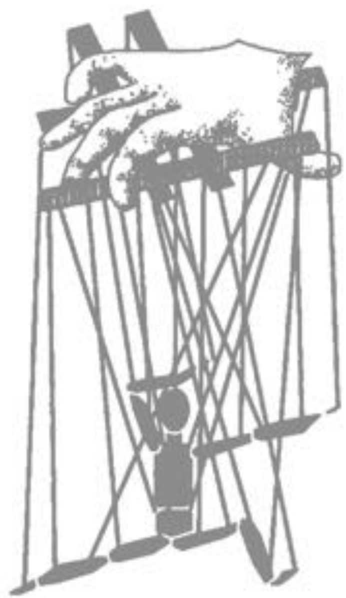
constraints imposed by nervous system

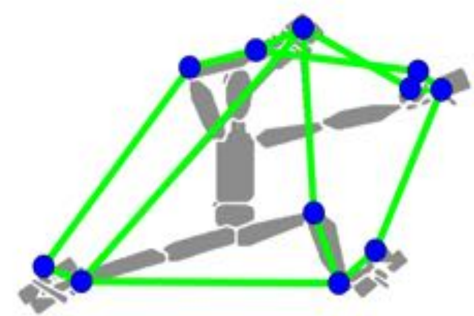


constraints imposed by musculoskeletal system

Controlling the musculoskeletal system

- Degree of freedom problem (DOFs) → 2^{600} activation patterns
- Motor control problem simplified if DOFs are coupled
- **Where do these couplings arise from?**

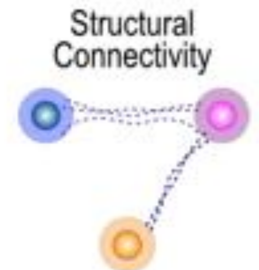




Use network analysis to investigate connectivity in neuromuscular system

Turvey (1990) *Am Psychol* 45

Functional connectivity analysis



Structural connectivity: pattern of anatomical links

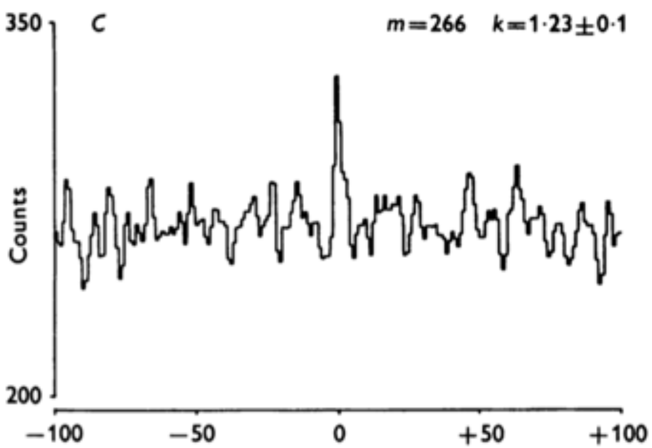
Functional connectivity: statistical dependencies

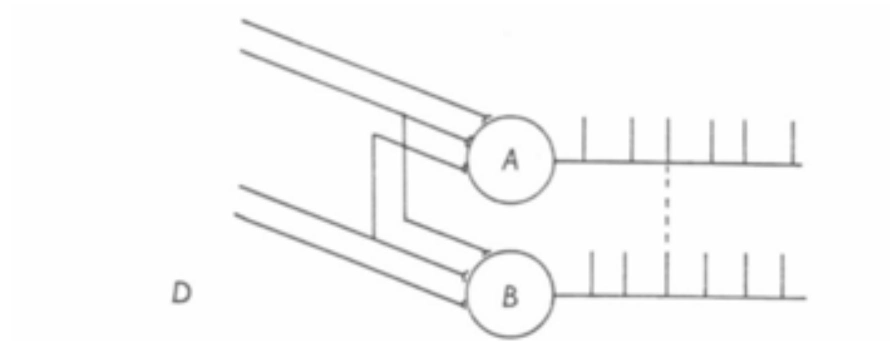
Effective connectivity: causal interactions

Friston (1994) *Hum Brain Mapp*

Spikes of alpha motor neurons are coupled

- Histograms show increased likelihood that two motor neurons spike together
- Simultaneous spikes due to last-order branch axons

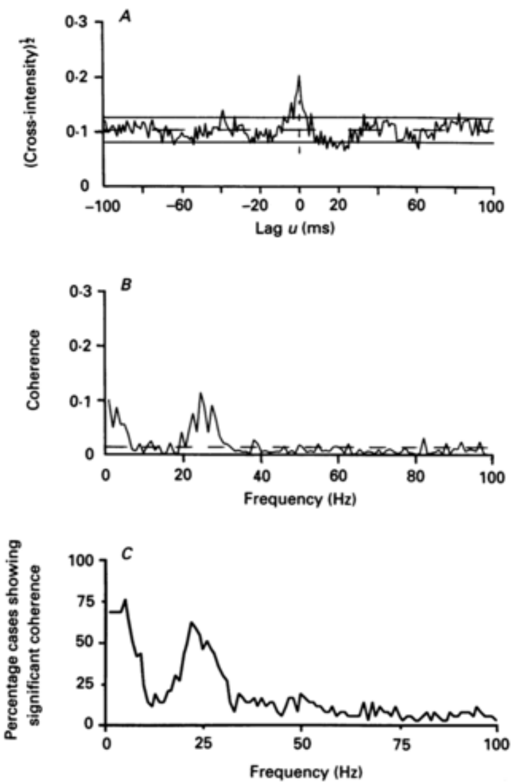


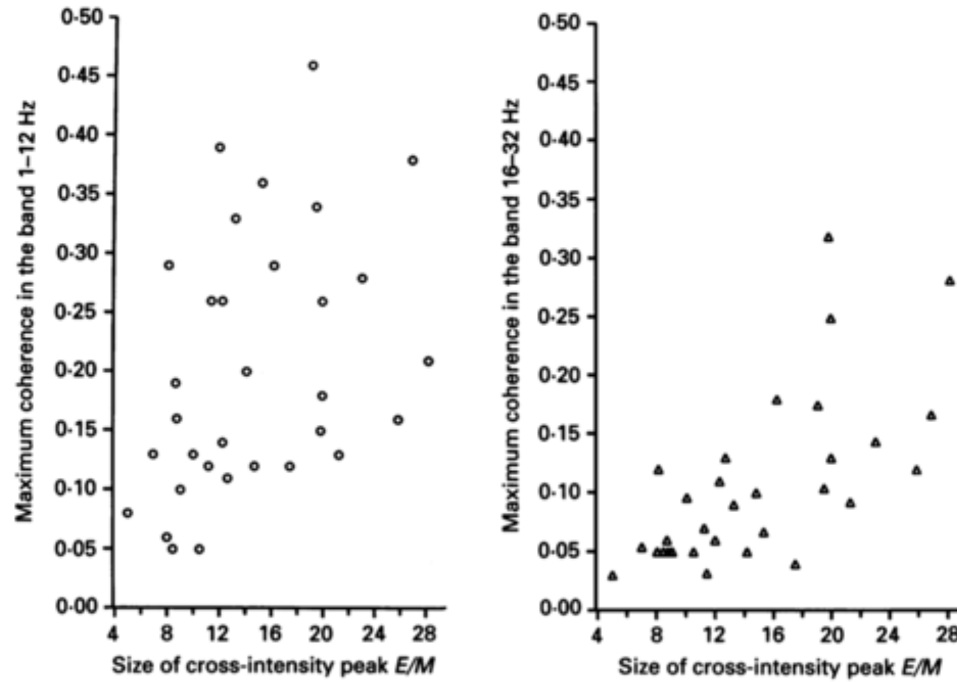


Sears and Stagg (1976) *J Physiol 263*

also in the frequency domain

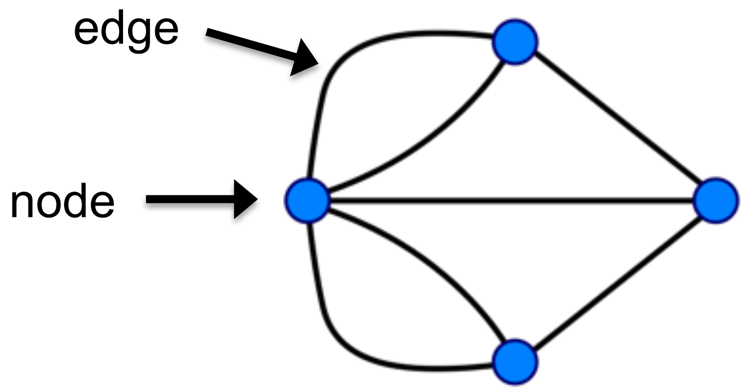
- Coupling between motor neurons can also be using coherence analysis
- Beta-band coherence associated with central peak of cross-correlation



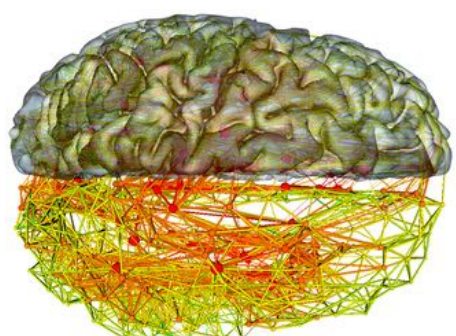


Farmer et al (1993) *J Physiol 470*

Complex network analysis



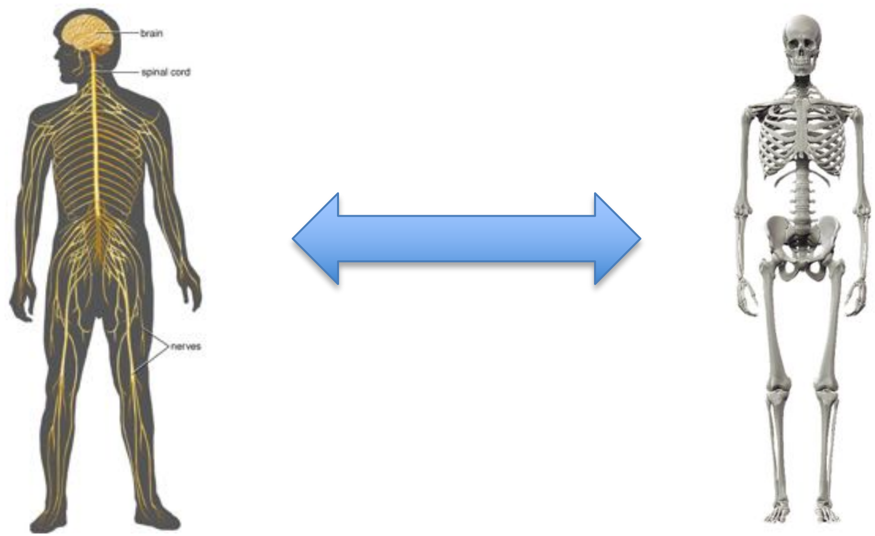
Brain networks



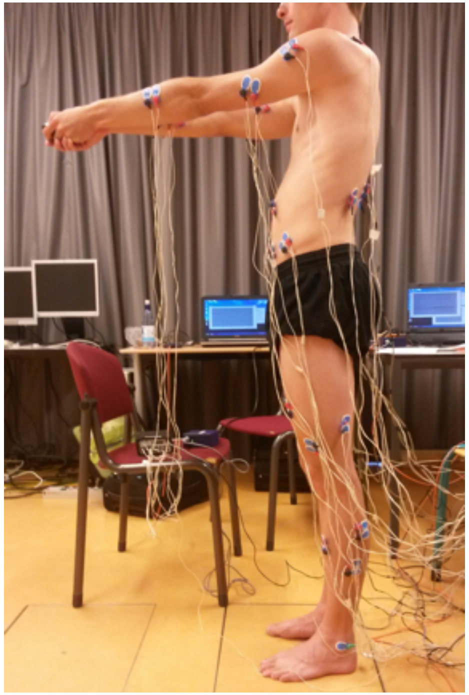
Social networks

Muscle networks

- Muscle are the nodes of the network
- Intermuscular coherence gives the edge weights for functional network
- Anatomical connections between muscles for anatomical network
- Compare functional and anatomical networks



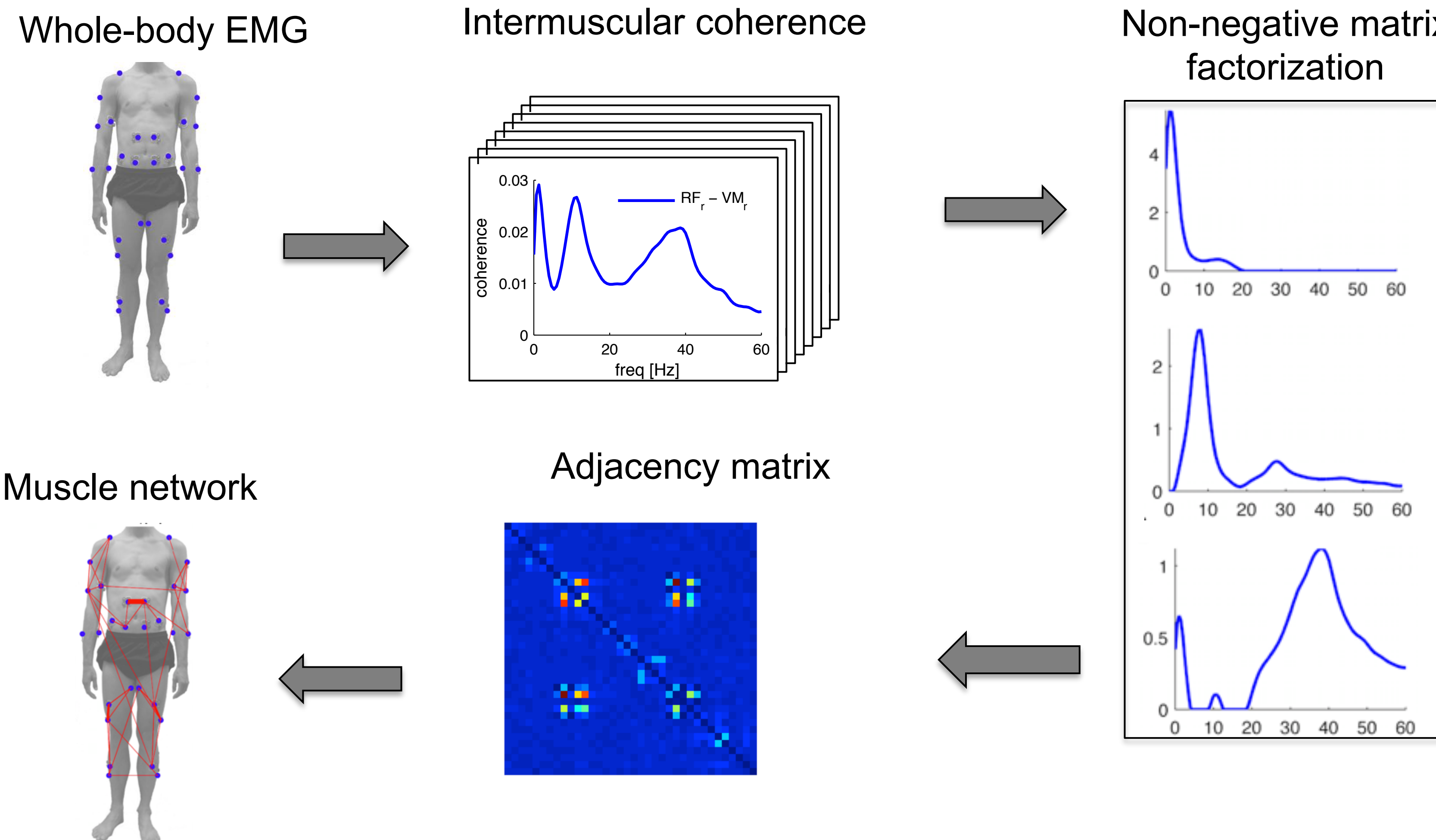
Experimental protocol



- Map networks of 36 muscles distributed across the body
- Record surface EMG from 14 participants during postural task
- Two experimental manipulations:
  1. Pointing (no, unimanual, bimanual)
  2. Stability (normal, anterior-posterior, medial-lateral)

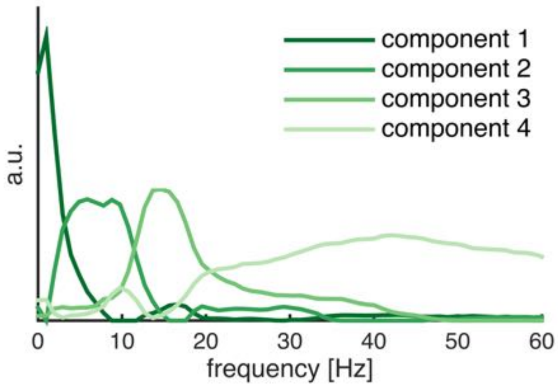
Data available at http://doi.org/10.5281/zenodo.1185196

Approach to map functional muscle networks



Boonstra et al. (2015) *Sci Rep* 5

Functional muscle network

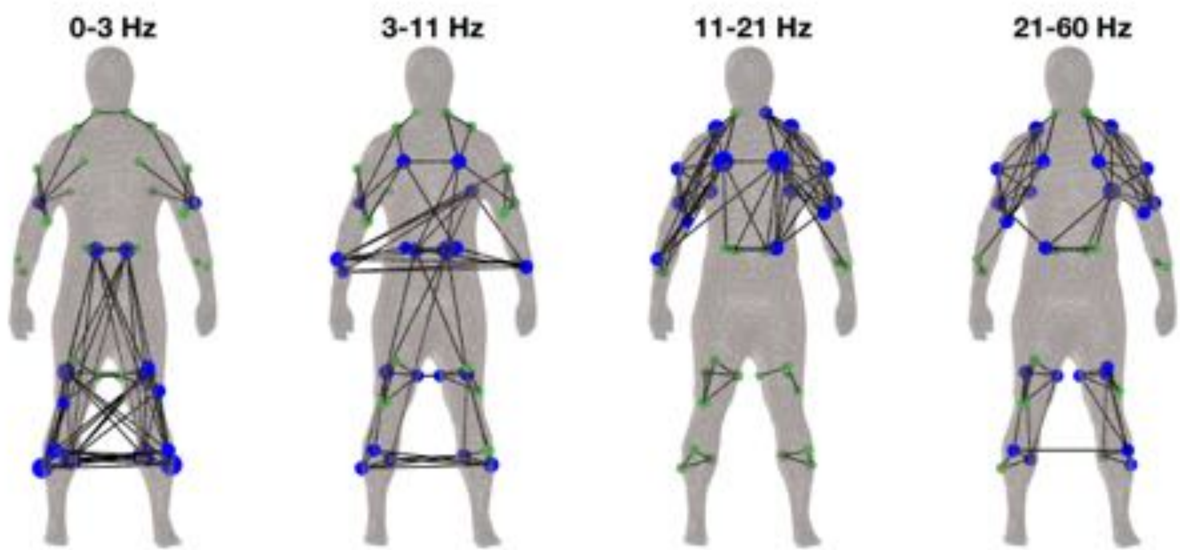


Extract four components using NMF

0-3, 3-11, 11-21 and 21-60 Hz

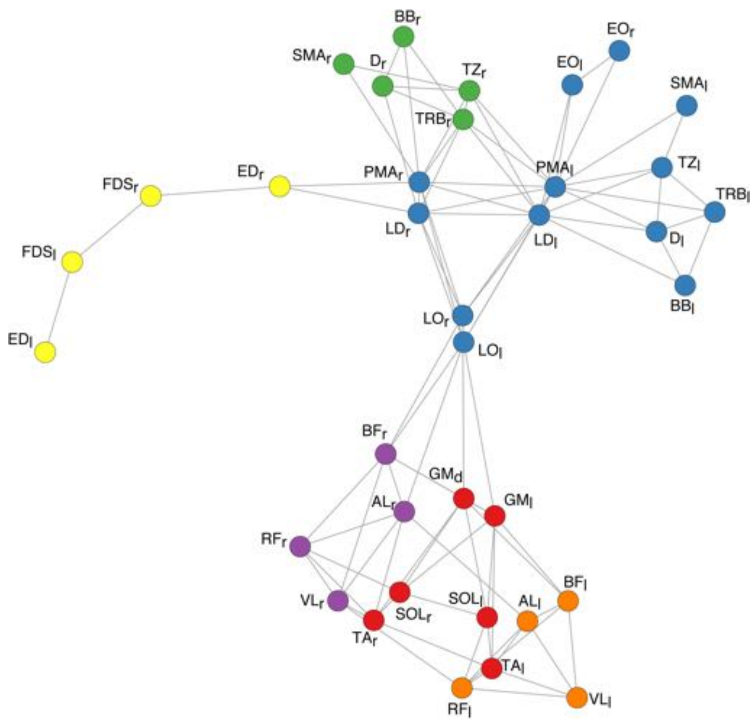
NMF gives edge weights at each frequency

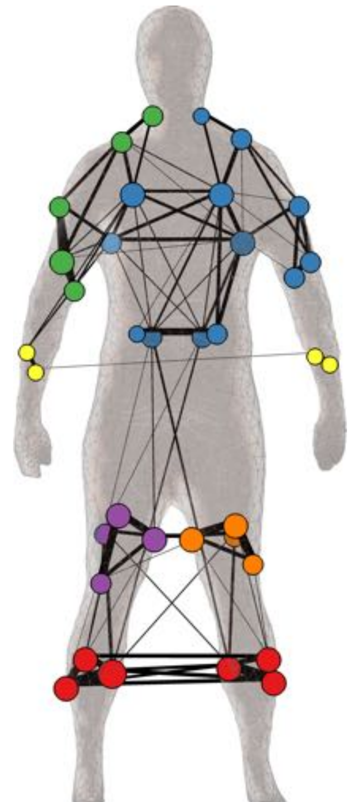
Distinct network topologies across frequencies



Functional muscle network

Community detection in multiplex networks (Didier et al, 2015)





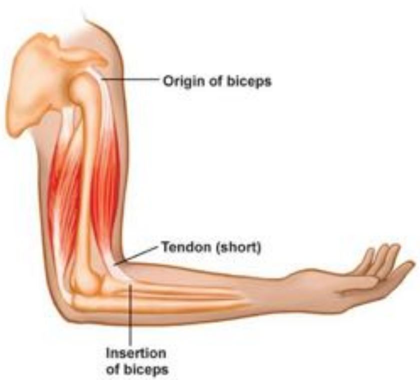
6 modules

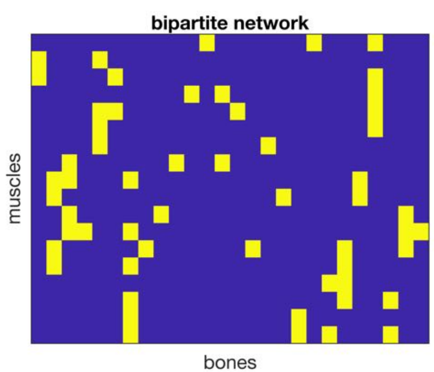
1. right upper arm
2. bilateral fore arm
3. Torso
4. right upper leg
5. left leg
6. bilateral lower leg

Kerkman et al (2018) *Sci Adv*

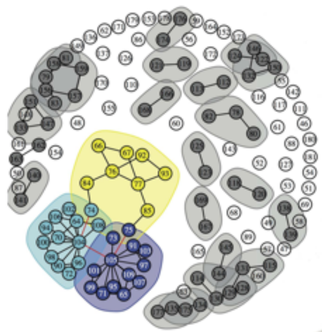
Approach to map anatomical muscle networks

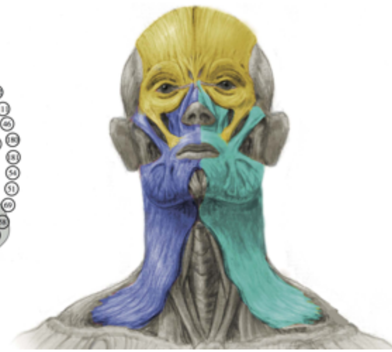
mapping origin and insertion of muscles





network of human head





Esteve-Altava et al (2015) *Sci Rep* 5

network of whole body

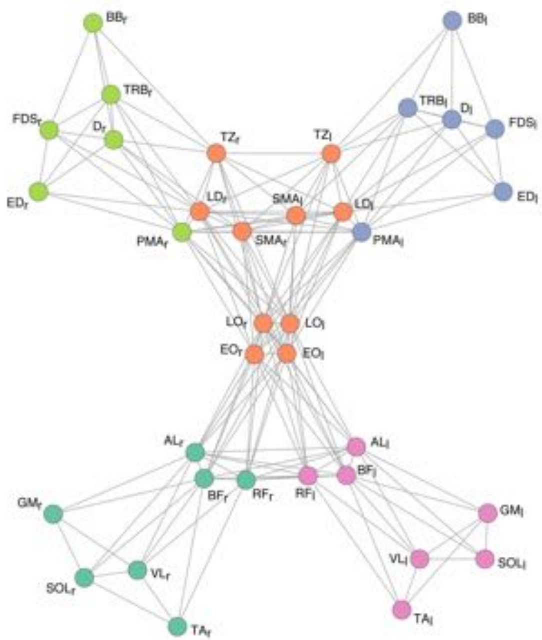
Murphy et al (2016) *arXiv 1612.06336*

Anatomical muscle network

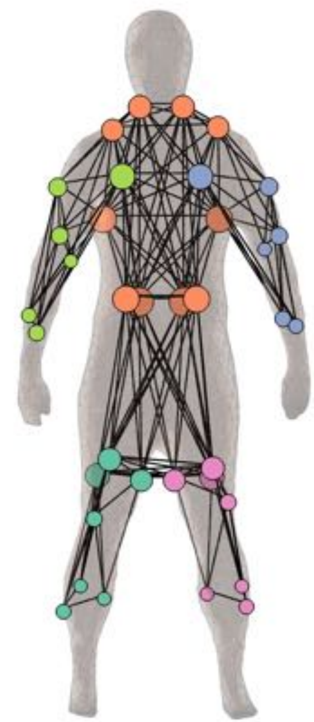
Map network for 36 muscles for which we recorded EMG

Modules extracted using Louvain method (Q = 0.38)

topological



spatial



5 modules

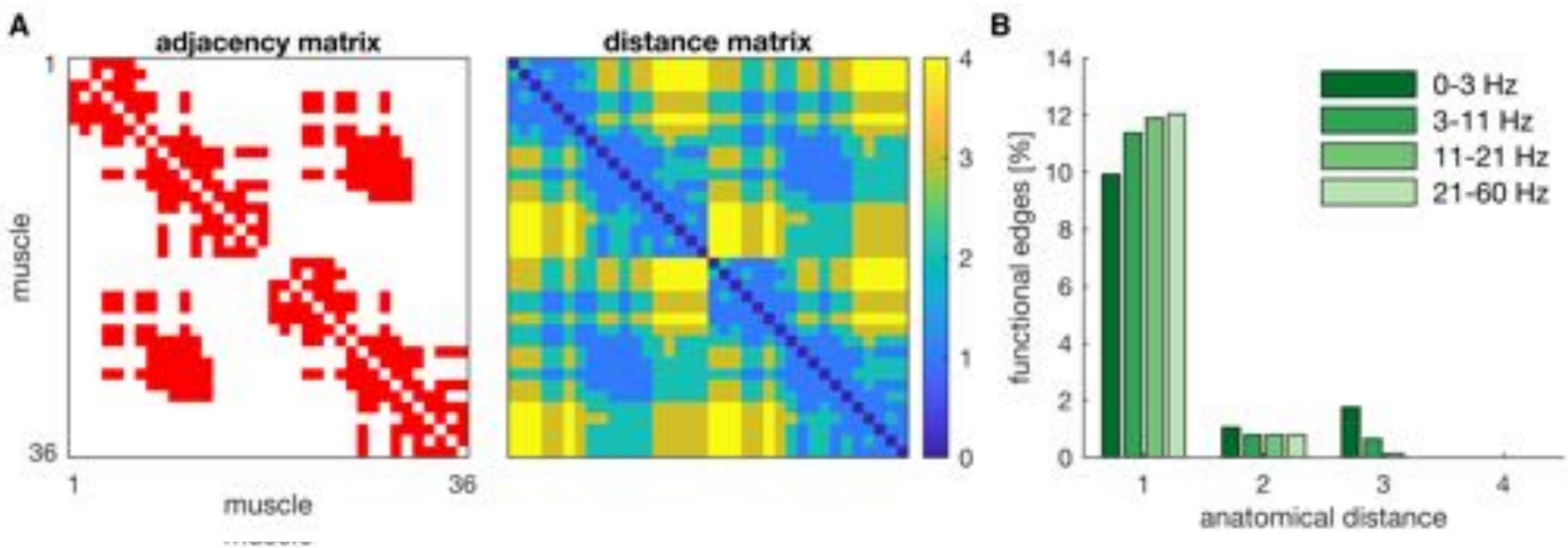
1. right arm
2. left arm
3. torso
4. right leg
5. left leg

Kerkman et al (2018) *Sci Adv*

Comparing anatomical and functional networks

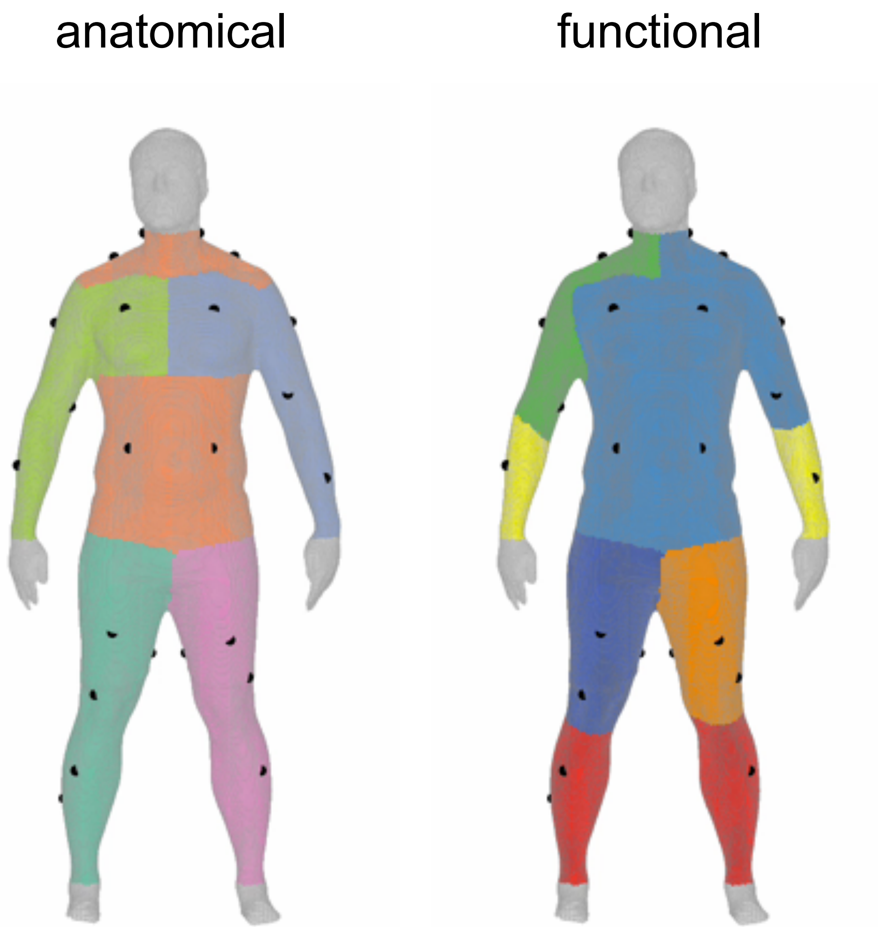
Estimate anatomical distance between muscles

Functional connectivity decreases with anatomical distance



Kerkman et al (2018) *Sci Adv*

Comparing anatomical and functional networks



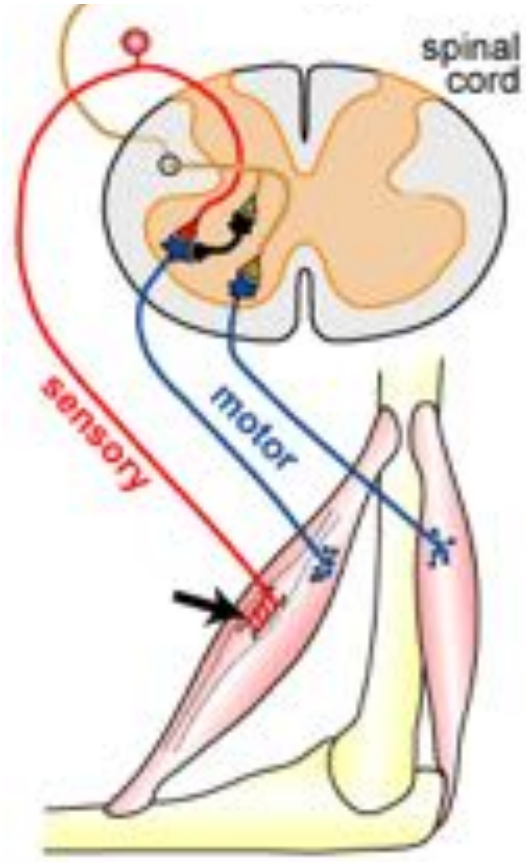
Similarities

- Similar community structure
- Adjusted Rand index = 0.37, $P < 0.001$

Differences

- Bilateral module of forearm muscles in functional networks
- Bilateral module of lower leg muscles in functional networks

Implications



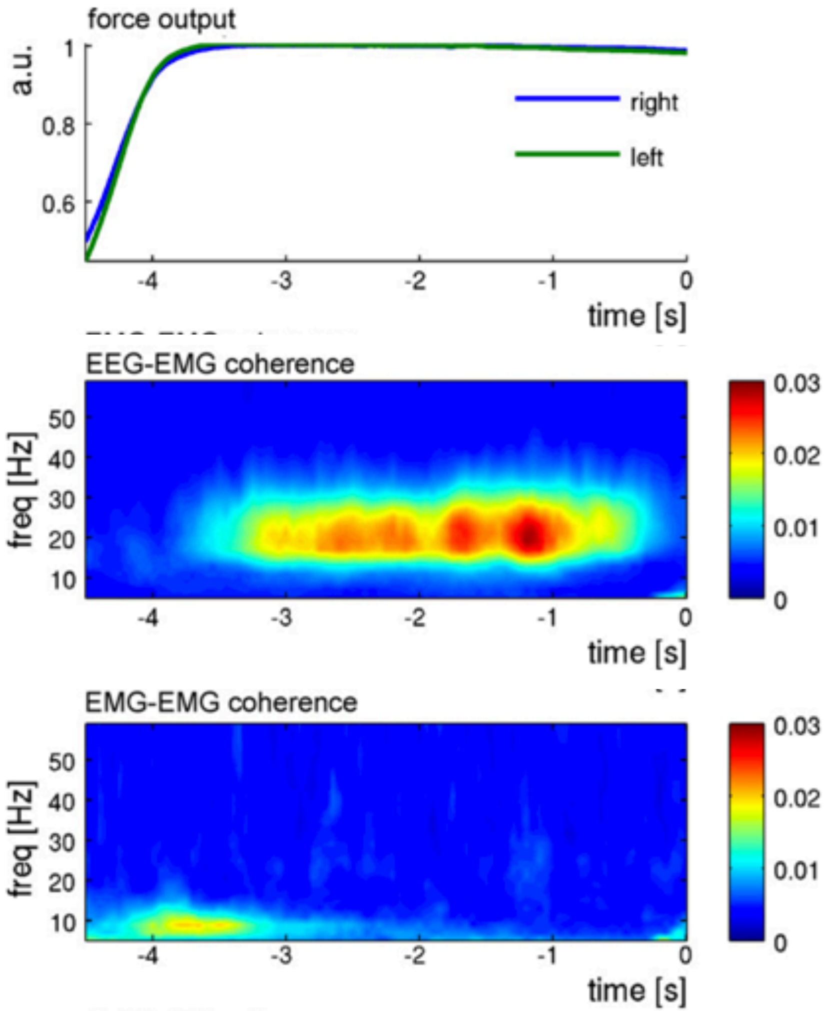
Intermuscular coherence

- Intermuscular coherence reflects **common input** to spinal motor neurons

Functional muscle networks

- Shaped by anatomical constrains of musculoskeletal system
- Bilateral functional connectivity reflect neural mechanisms/modulations

Task-related changes in functional connectivity



Participants generate same force with both hands

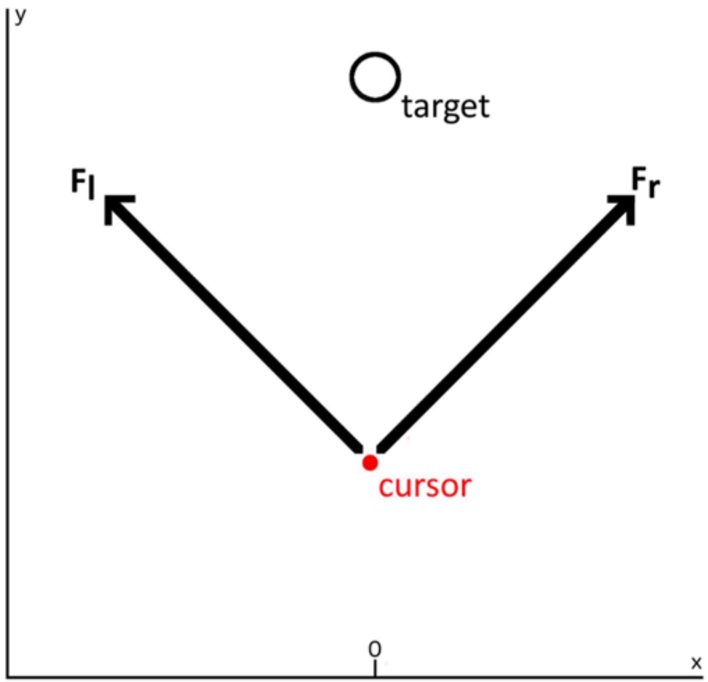
Corticomuscular coherence at ~20 Hz between motor cortex and hand muscle → **corticospinal pathway**

Intermuscular coherence at ~10 Hz between bilateral hand muscles → **non-cortical origin**

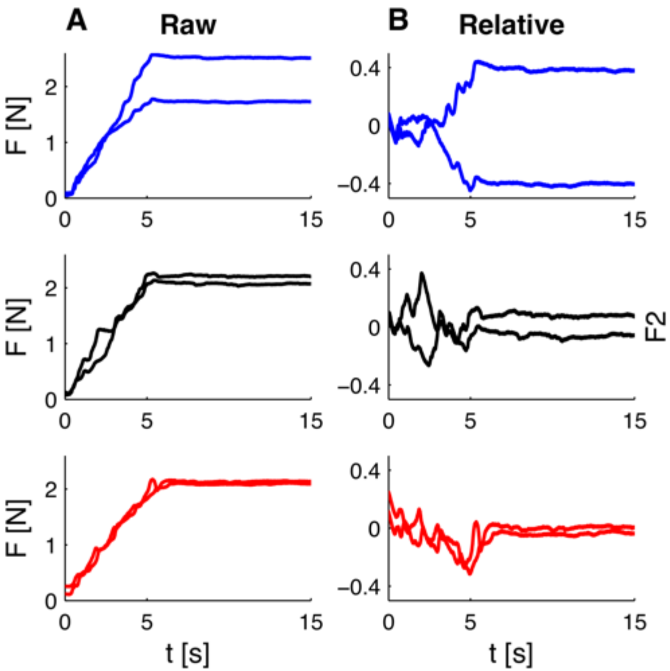
Boonstra et al, 2009, *Neurosci Lett*

Task-related changes in functional connectivity

Control cursor on screen by coordination left and right force



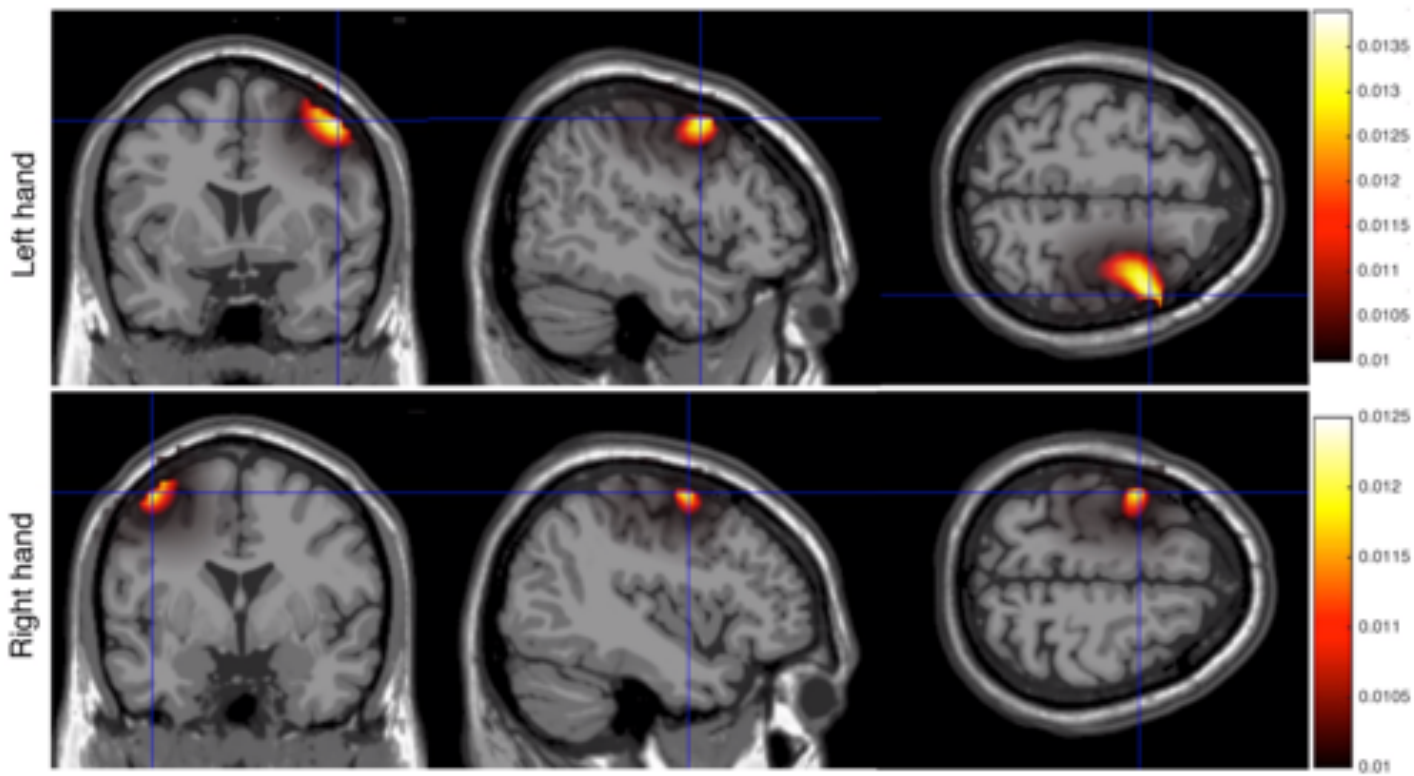
Experimentally manipulate the level of bimanual coordination



De Vries et al, 2016, *J Neurophysiol*

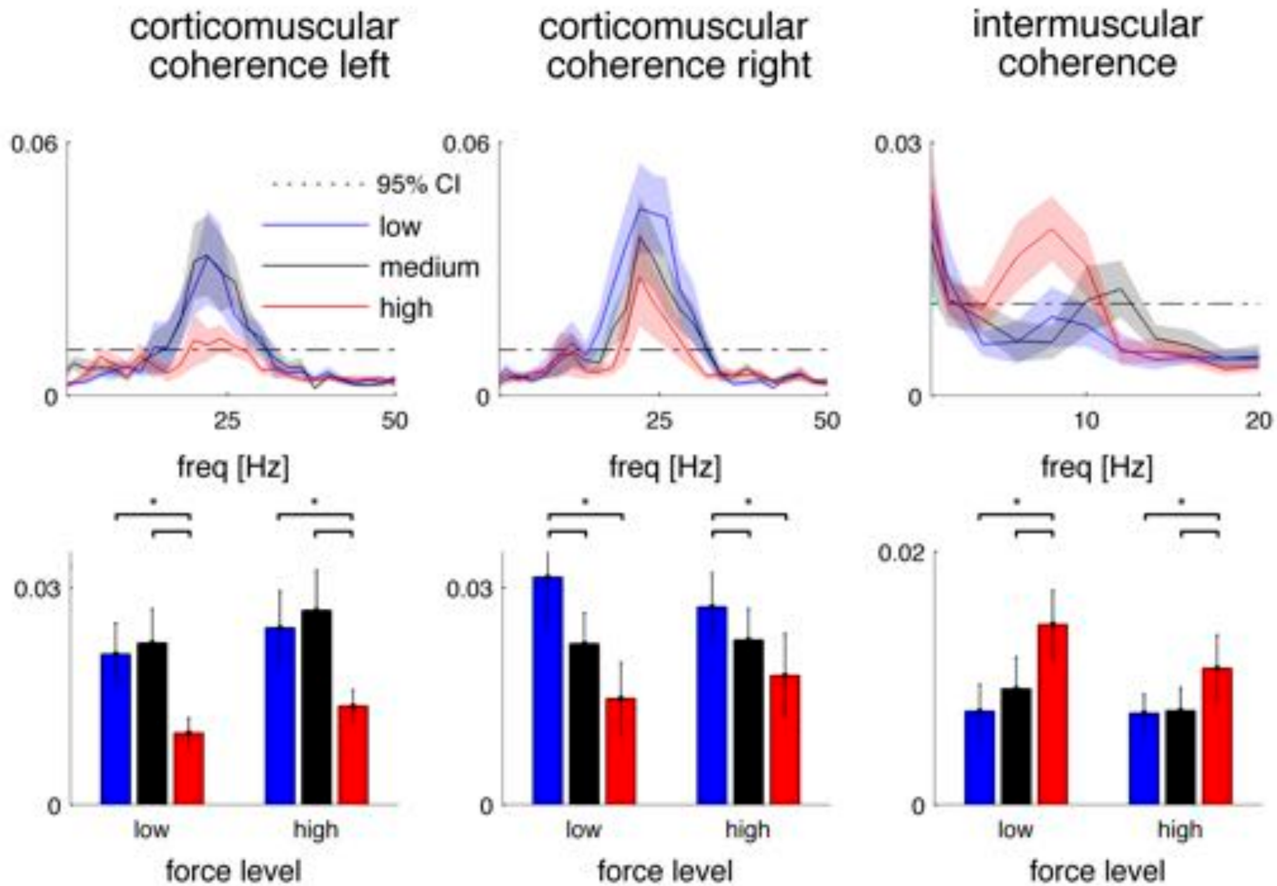
Task-related changes in functional connectivity

Source reconstruction of EEG shows activity in contralateral sensorimotor cortex



De Vries et al. 2016, *J Neurophysiol*

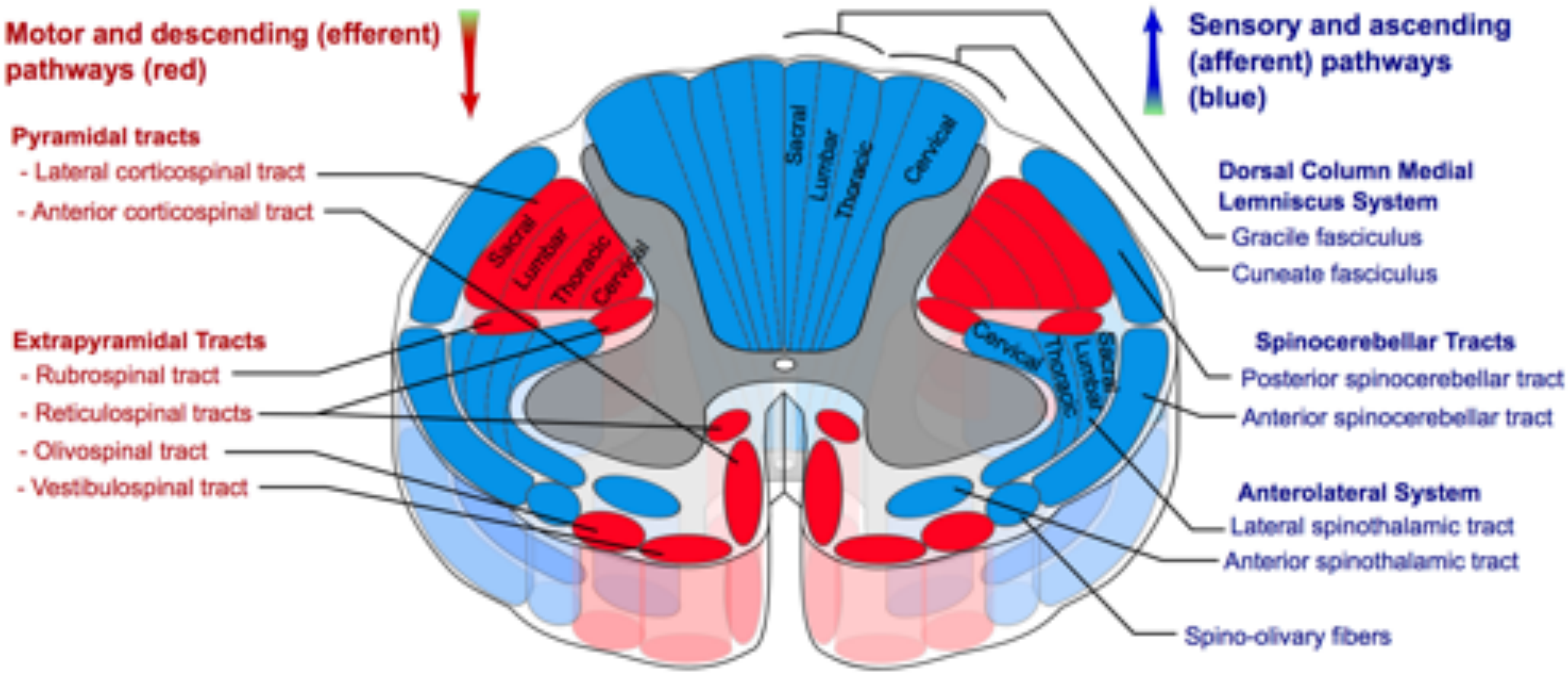
Task-related changes in functional connectivity



Suggest flexible involvement of two distinct pathways

De Vries et al, 2016, *J Neurophysiol*

Multiple ascending and descending pathways



Conclusions

- Functional connectivity and network analysis to map and compare different types of connections between brain and muscle
- Functional connectivity analysis shows coherence at multiple distinct frequencies
- Functional connectivity shaped by the anatomical constraints of musculoskeletal system
- Task-dependent changes in functional connectivity reveal the contribution of different neural pathways
- Study functional integration (i.e. coupling of distributed areas of CNS into coherent patterns) within the human sensorimotor system

Collaborations

Jennifer Kerkman

Ingmar de Vries

Leonardo Gollo

Luca Faes

Andreas Daffertshofer

Dick Stegeman

Michael Breakspear

Daniele Marinazzo

E: tjeed.boonstra@maastrichtuniversity.nl; T: @TjeerdWBoonstra