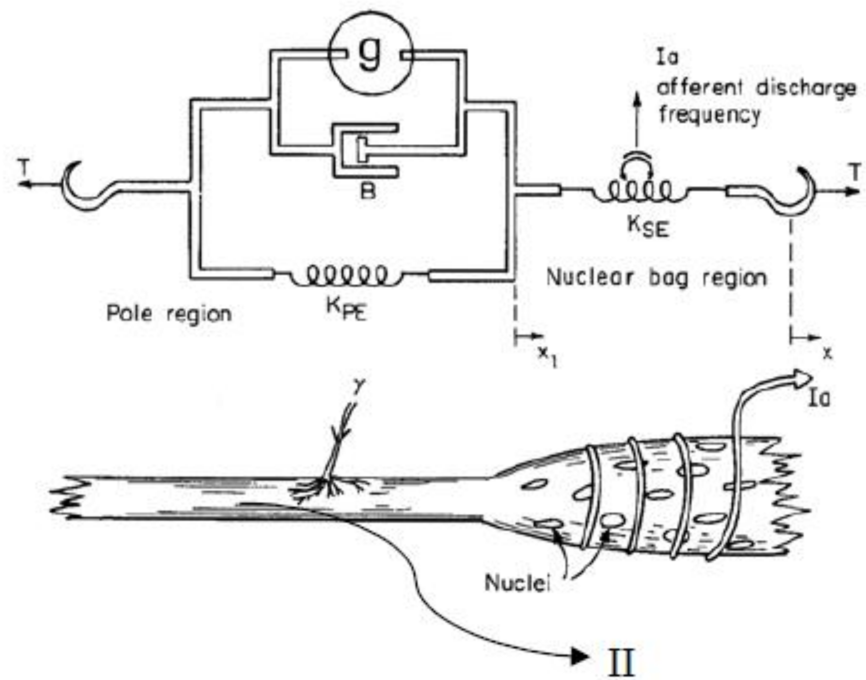
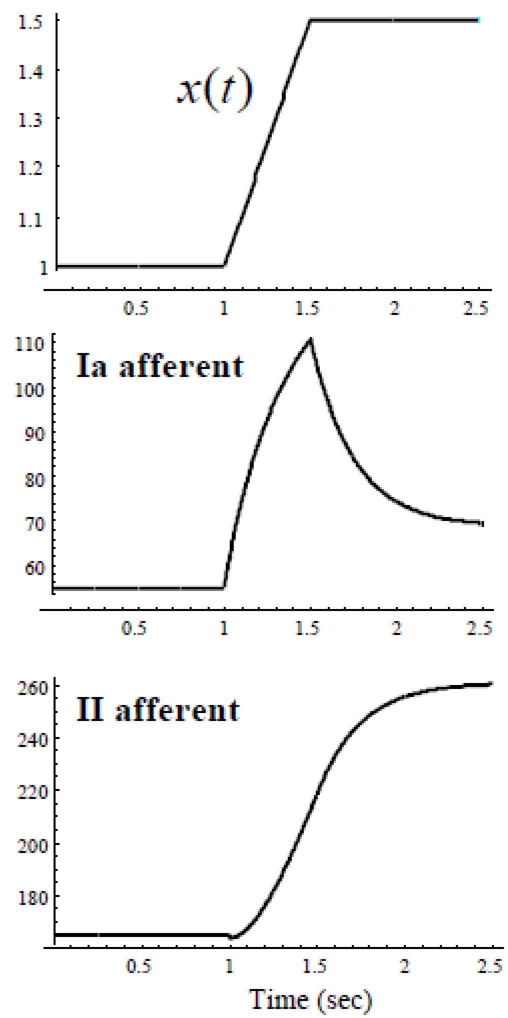
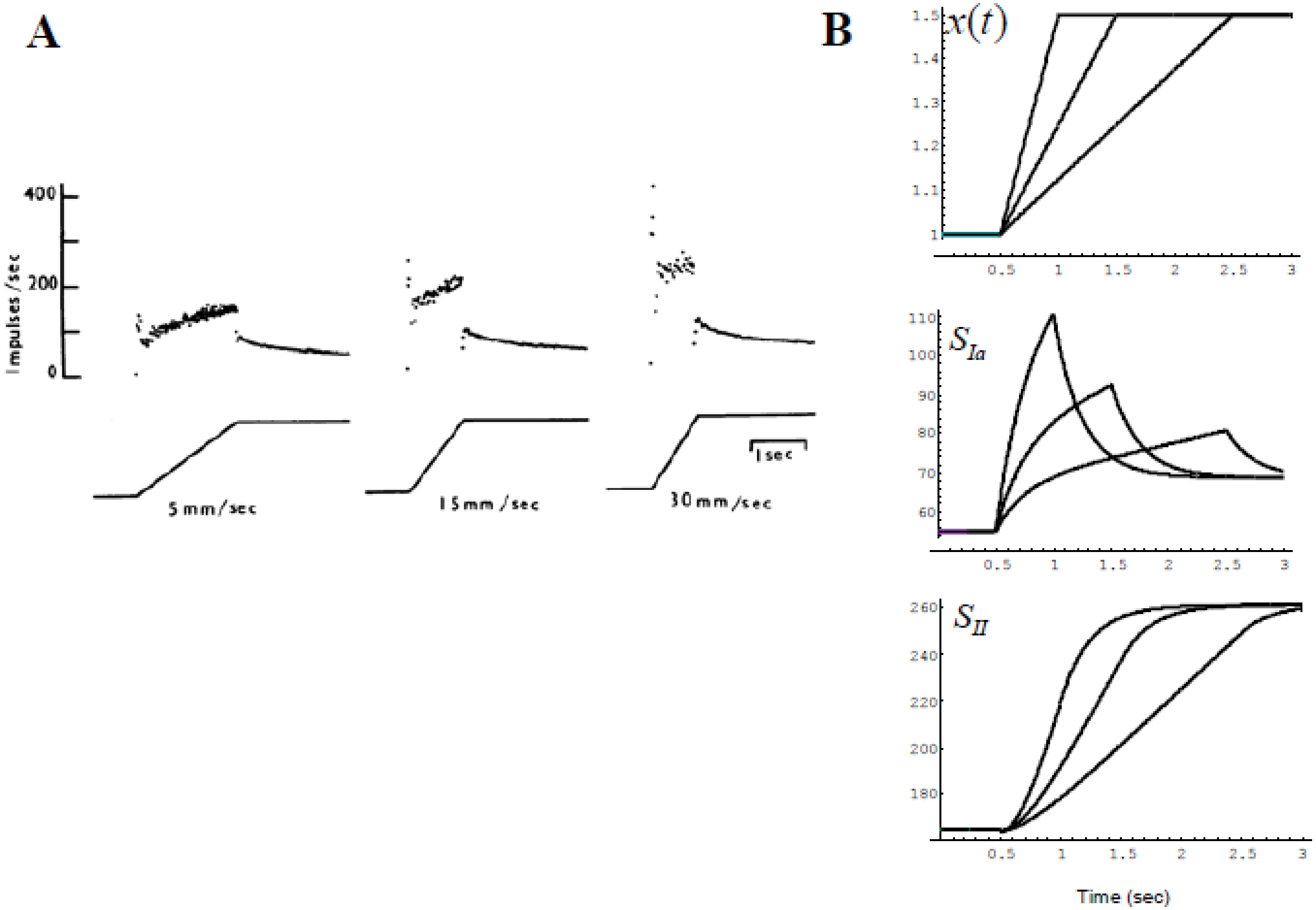
Spindle model



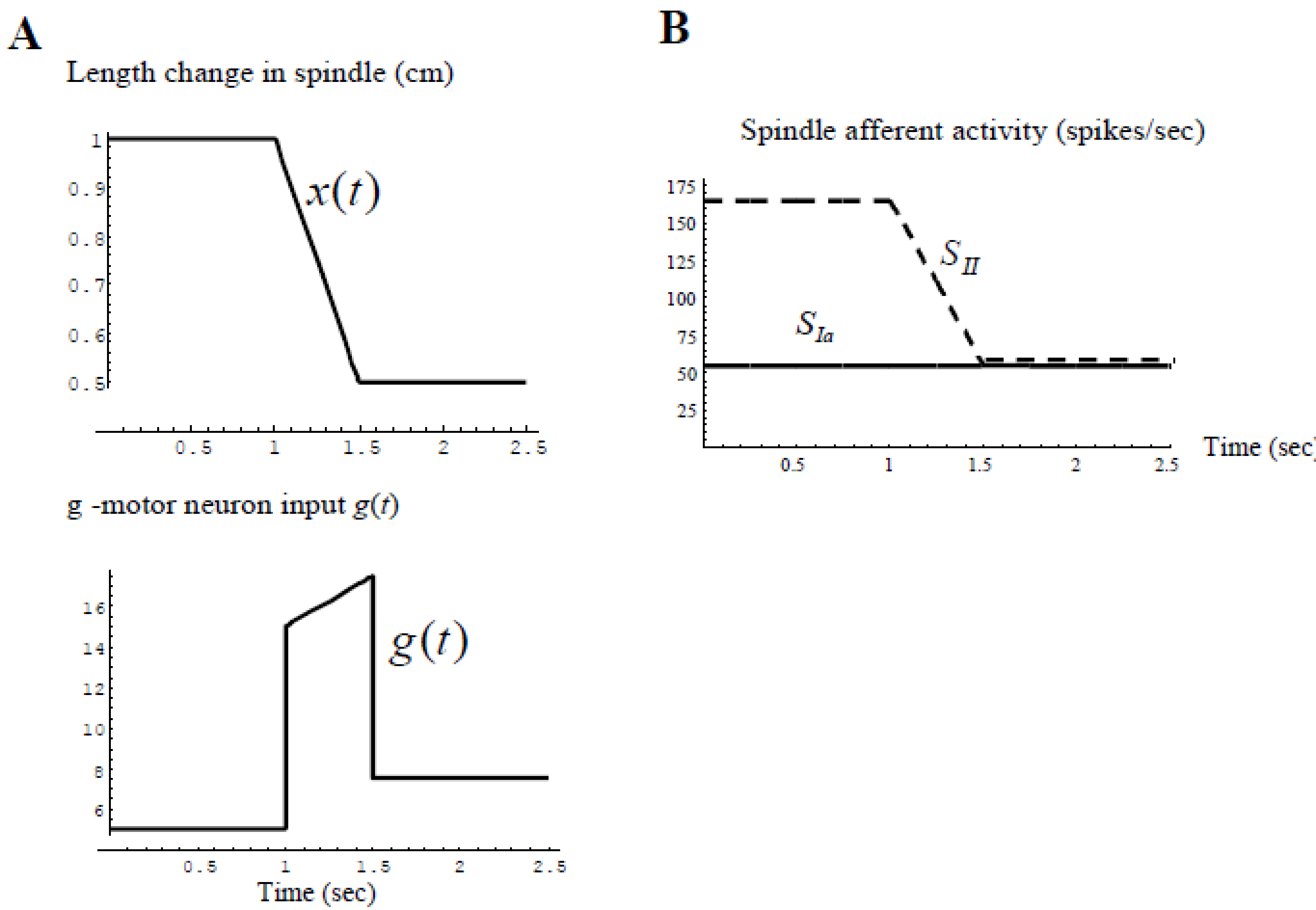
Simulation of spindle model



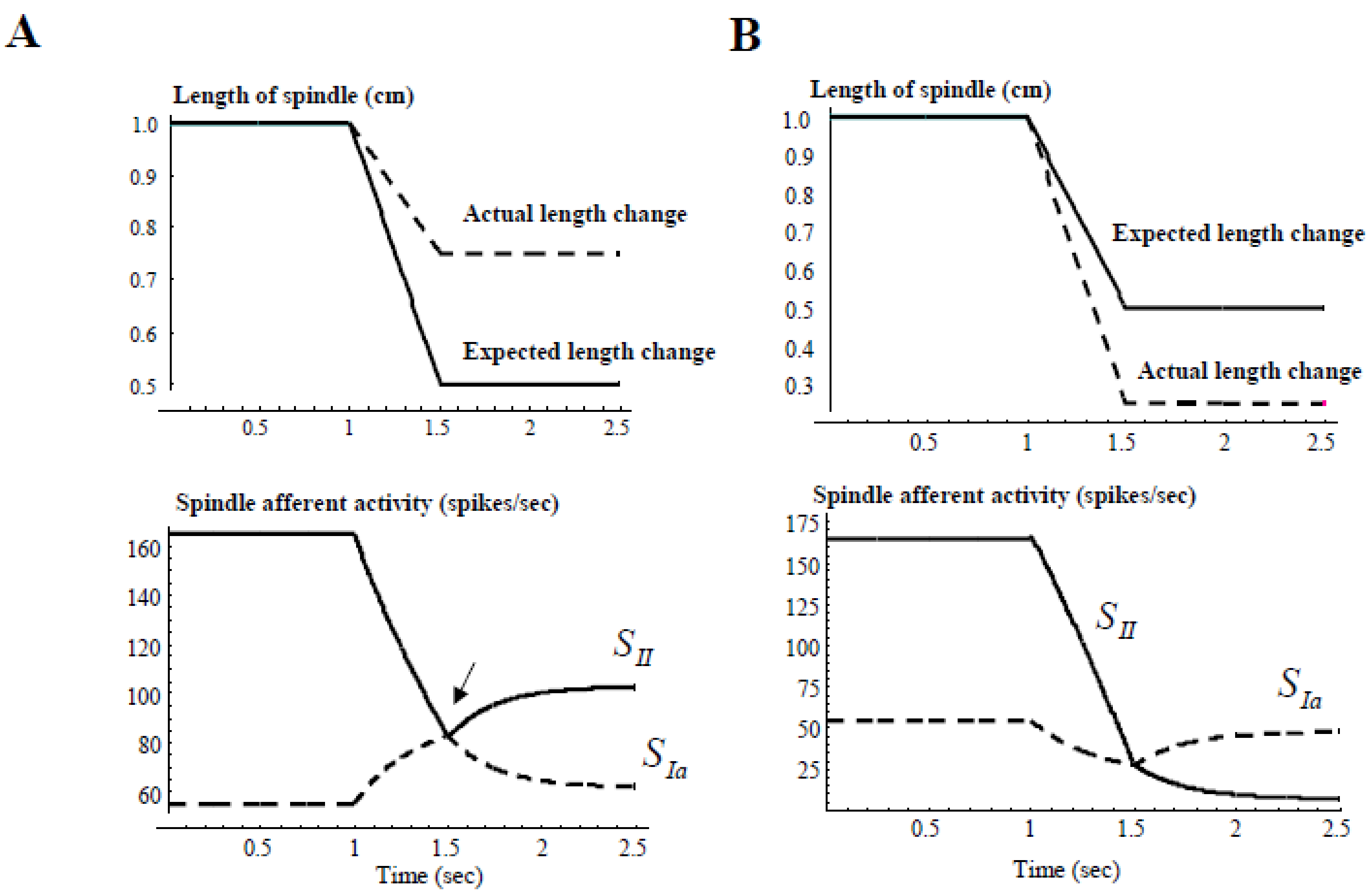


A
B
Impulses/sec
400
200
0
5 mm/sec
15 mm/sec
30 mm/sec
1 sec
$x(t)$
S_{Ia}
S_{II}
Time (sec)

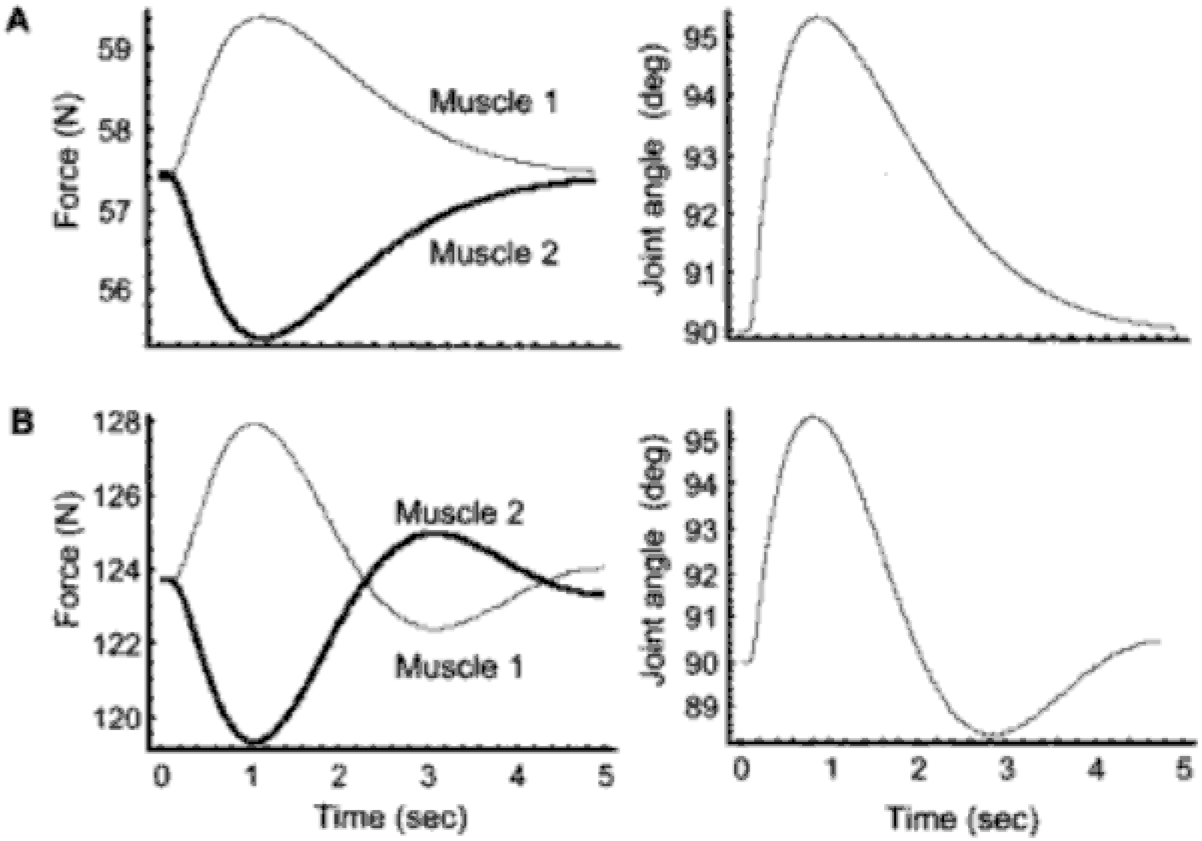
Simulation with gamma-activation



Error detection



Stimulation & stiffness

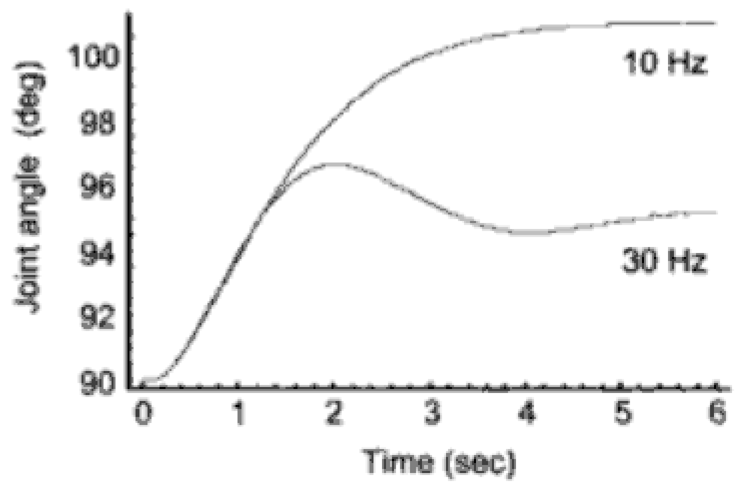


10Hz

30Hz

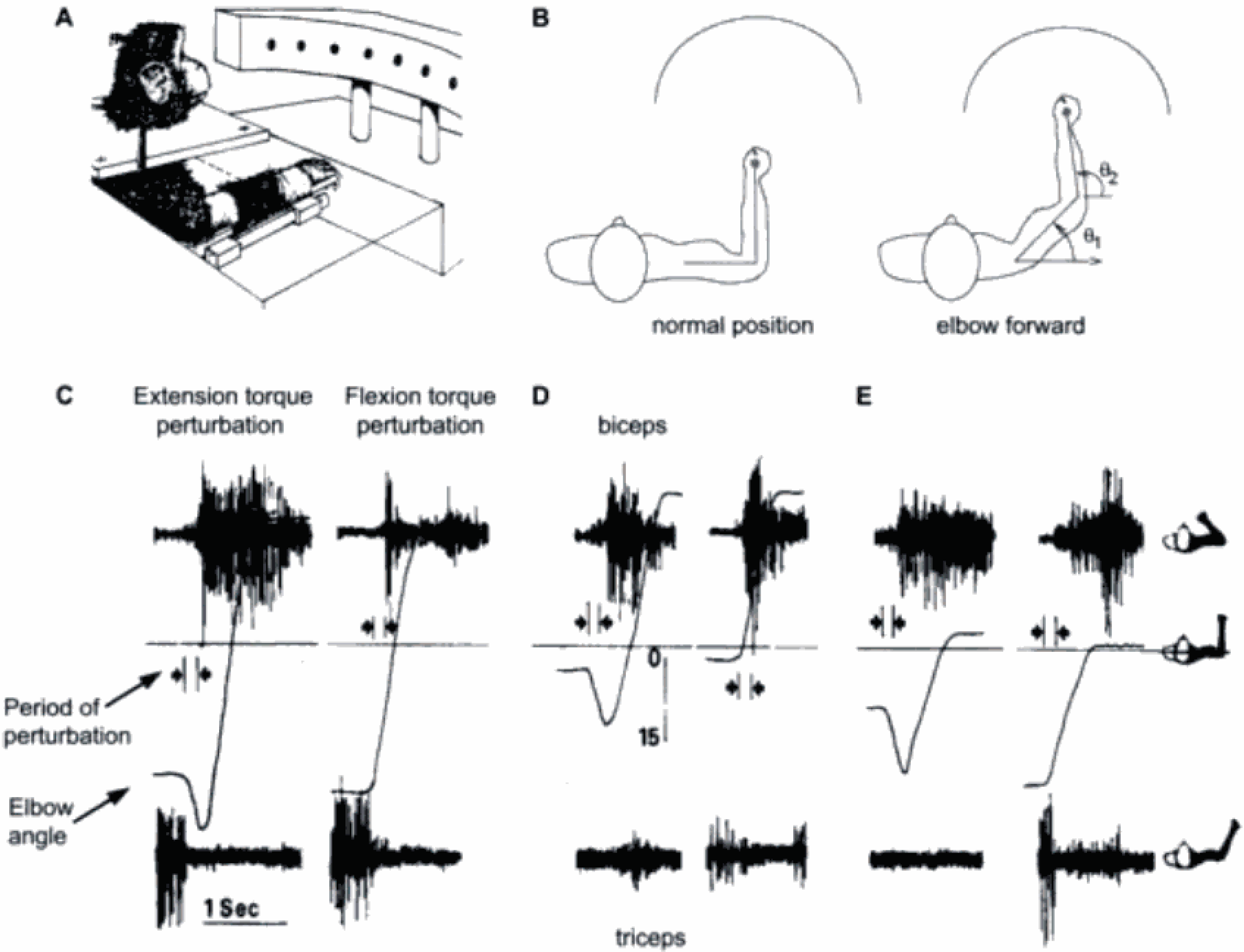
Step response

Stim: 0.1Nm



Stiffness ~0.01Nm/deg

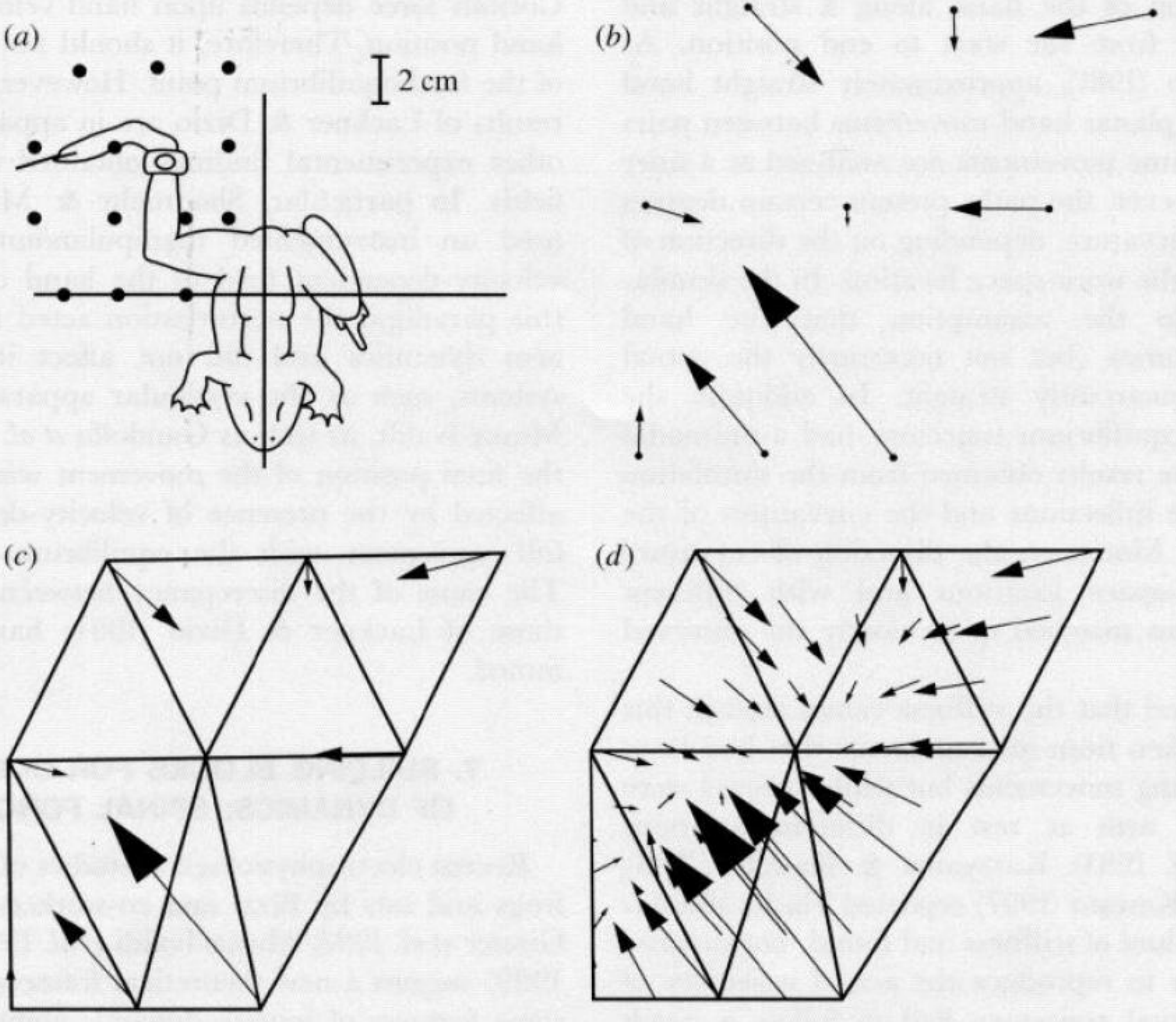
Stiffness ~0.02Nm/deg

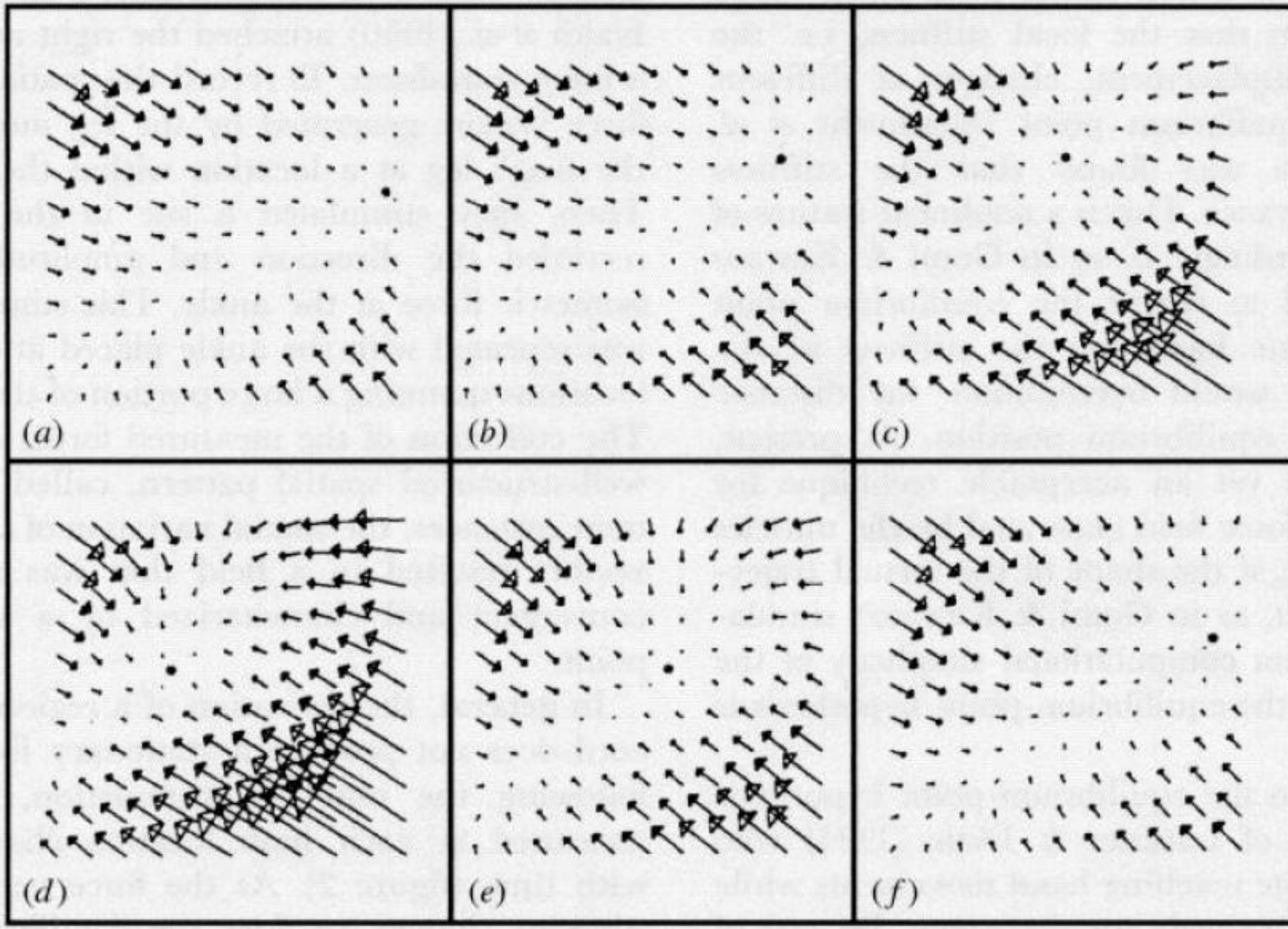


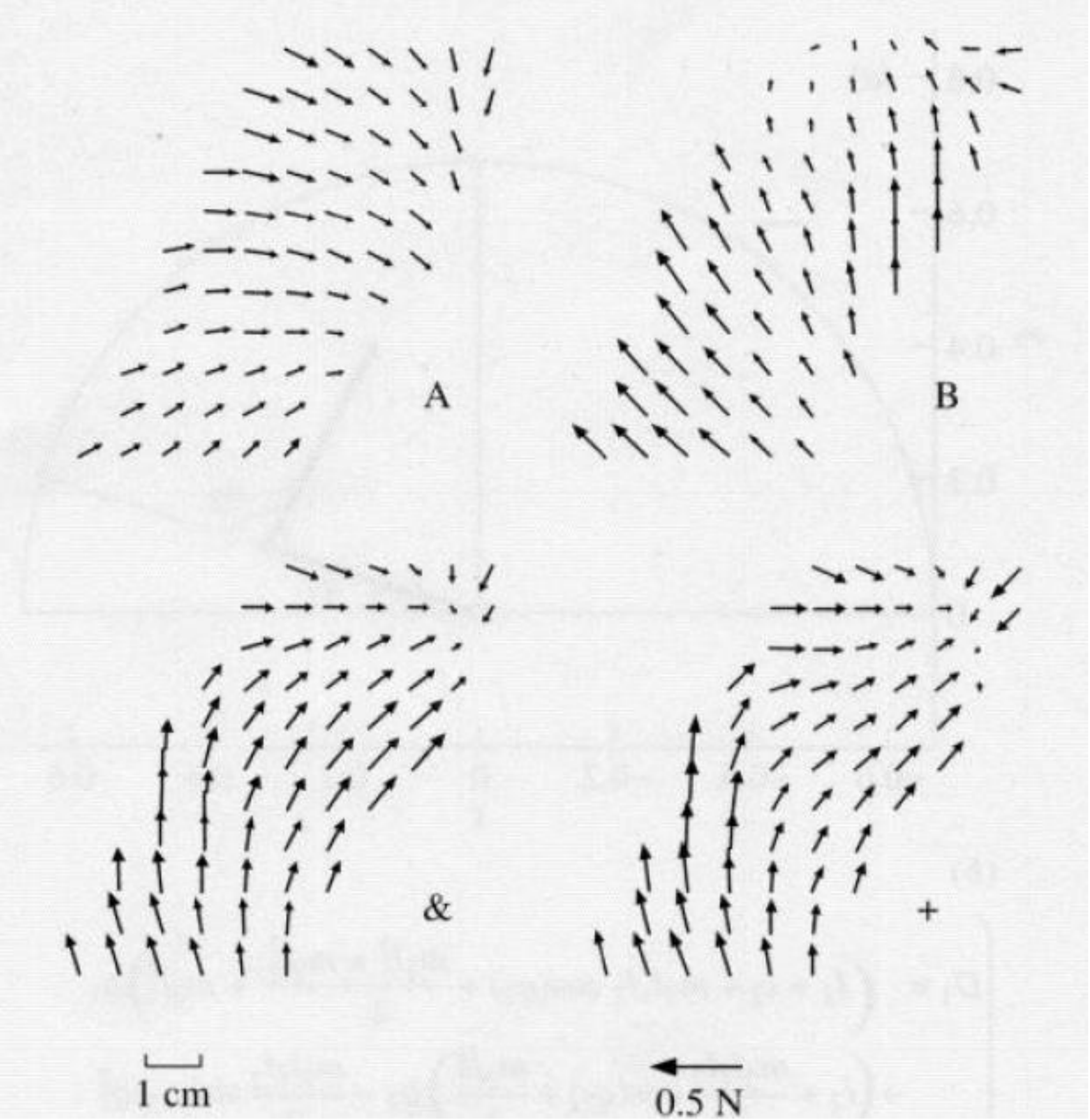
Polit & Bizzi 1979

Various experiments

- Polit & Bizzi (described)
- Mussa-Ivandi & Bizzi
  - Spinal cord stimulation
  - Primitives?
- Graziano
  - Cortical stimulation
  - Primitives?

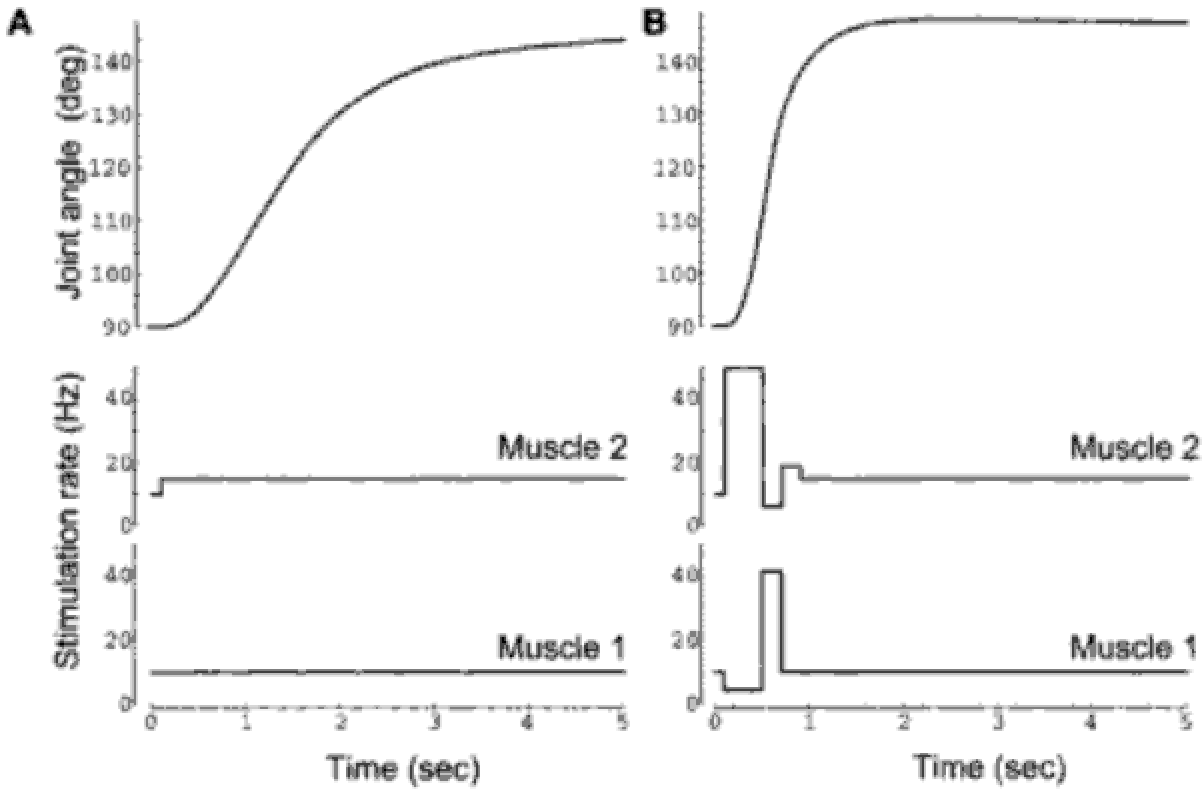

(a)
2 cm
(b)
(c)
(d)


(a)
(b)
(c)
(d)
(e)
(f)



A
B
&
+
1 cm
0.5 N

Three-burst pattern



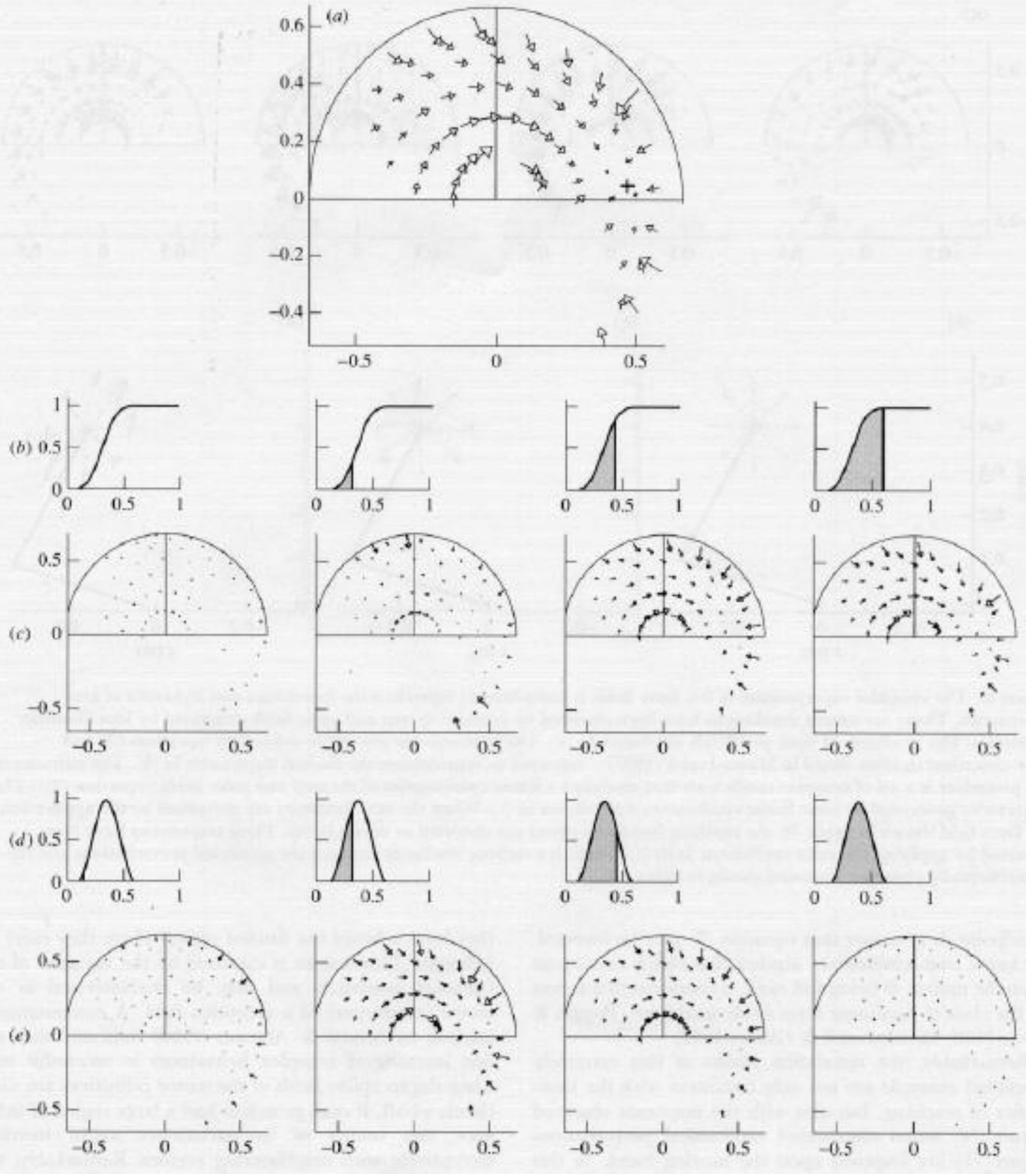
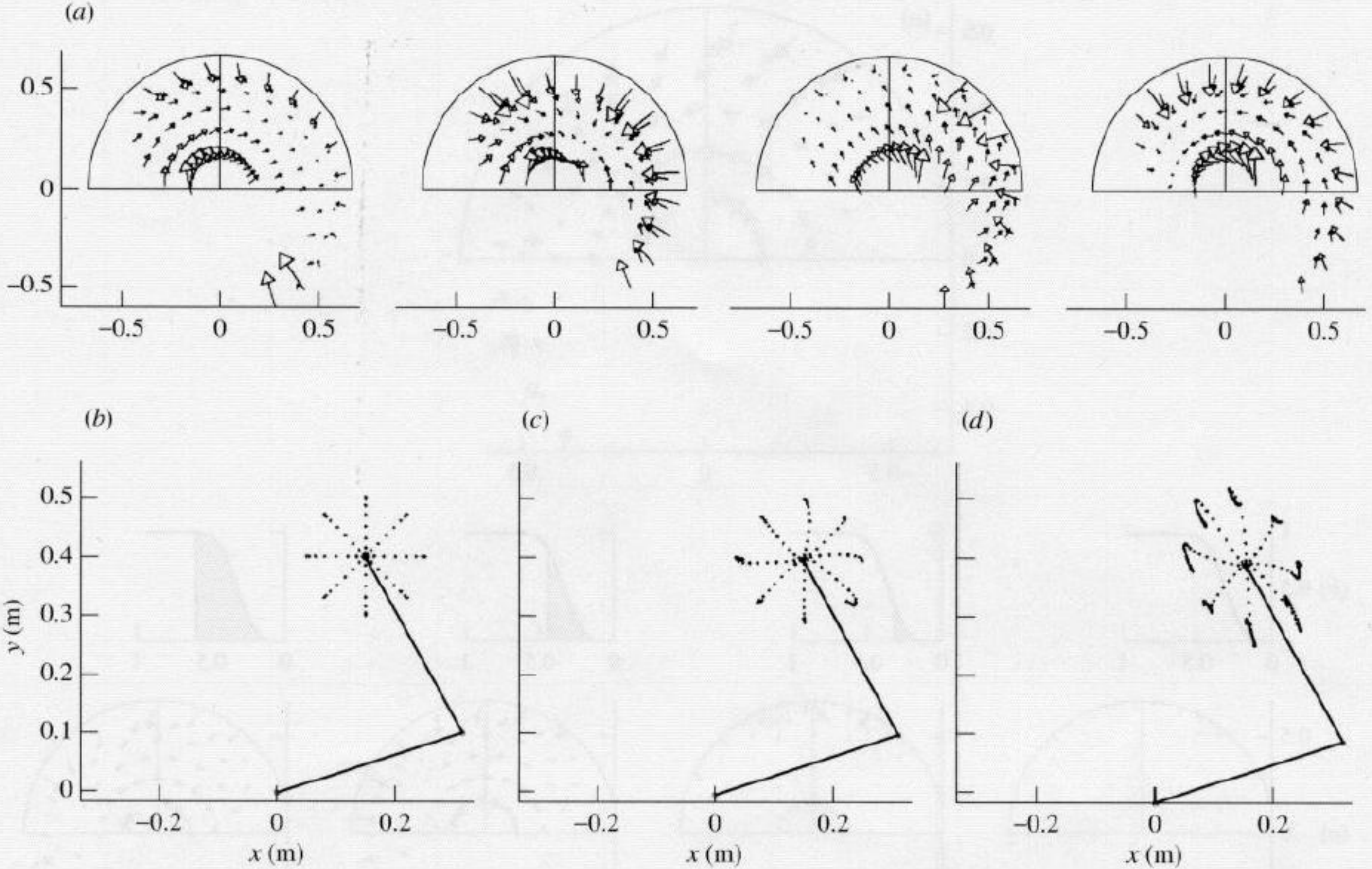
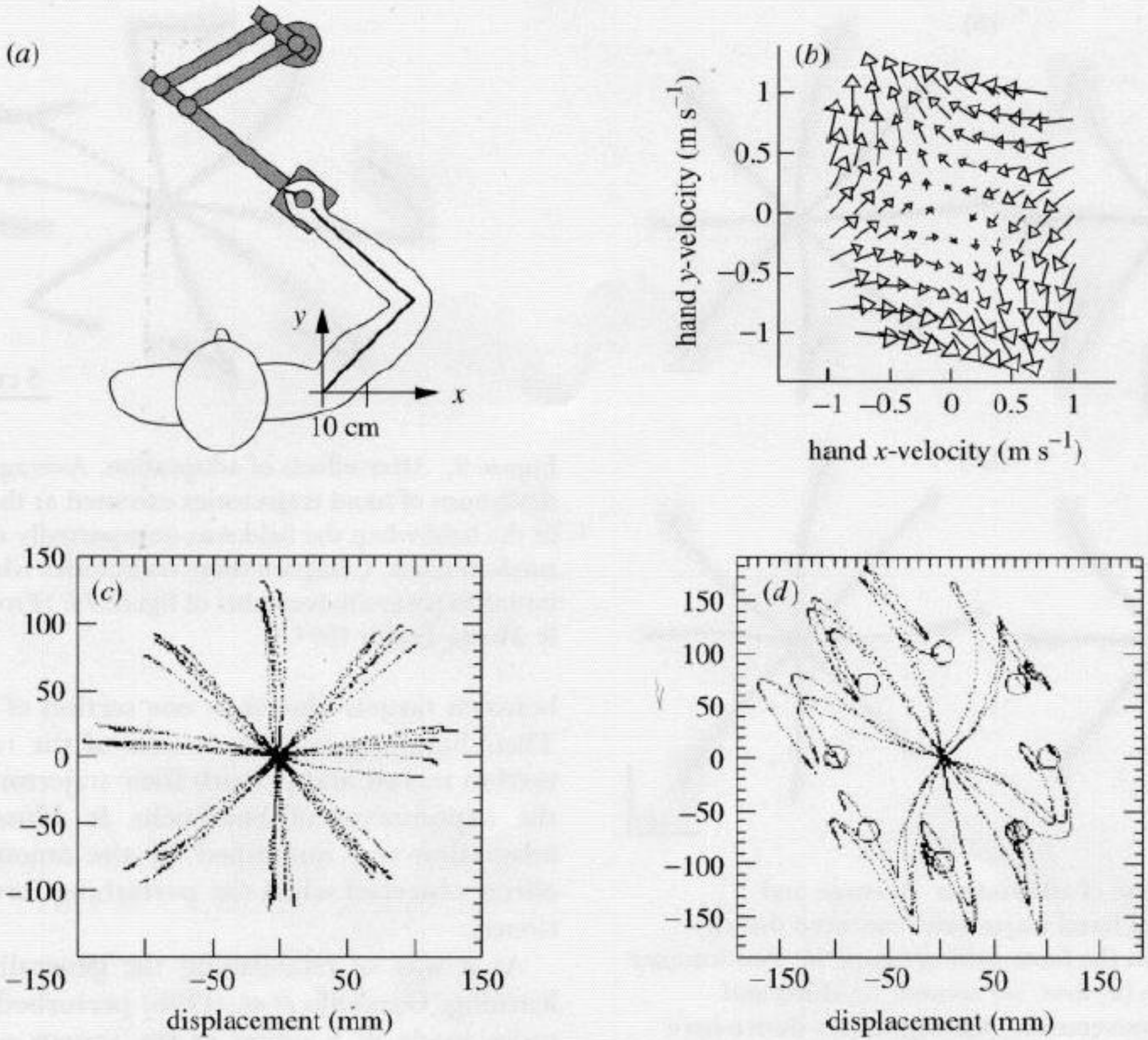


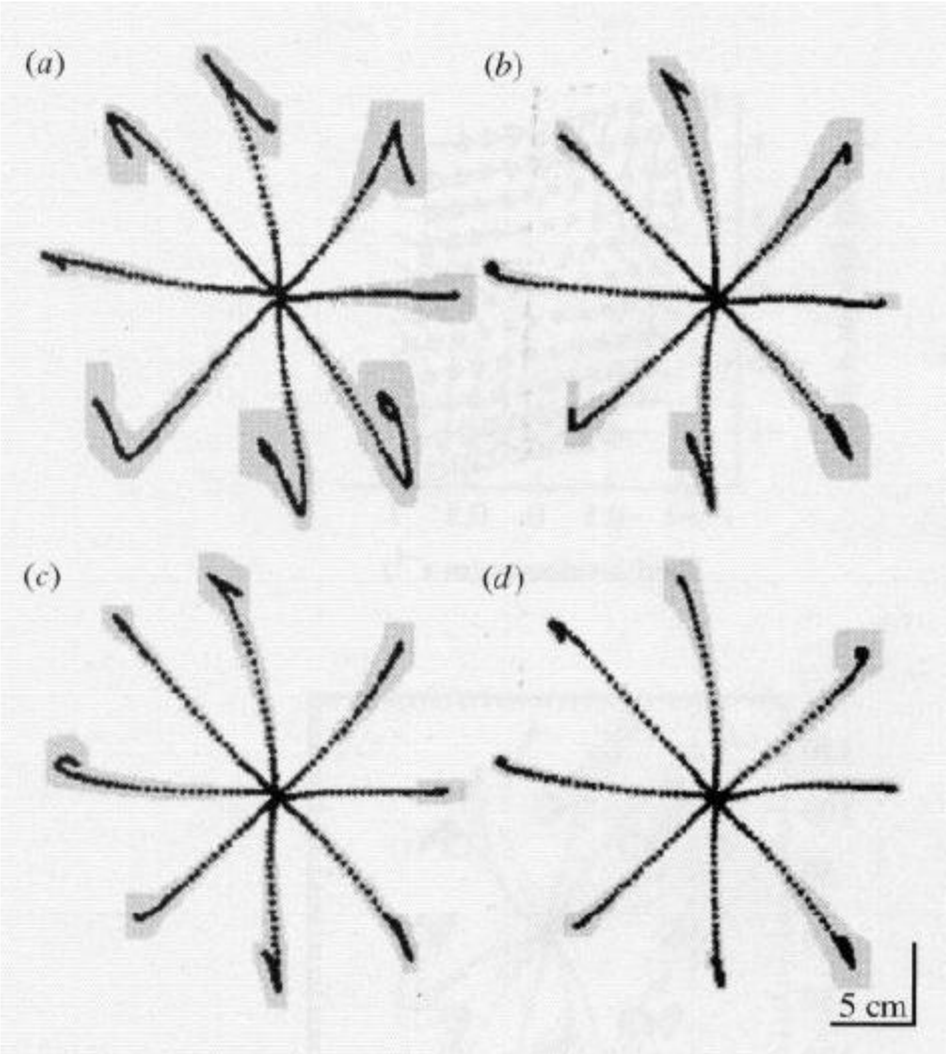
Figure 5. A simplified model of spinal force fields. The force field in (*a*) is the gradient of a Gaussian potential function defined over the angular coordinates of the mechanism in figure 4. The force vectors converge towards a stable equilibrium point indicated by the small cross. Gaussian potentials are smooth functions defined over the entire limb work-space. The gradient defines a stable equilibrium and the forces grow in amplitude within a region defined by the variance of the Gaussian potential. This behaviour simulates the tendency of muscle-generated forces to grow until a critical amount of stretch is reached. At that point the forces yield and then begin to decline. It is worth observing that in this mechanical context, the variance of the Gaussian potential has the dimension of compliance (the inverse of stiffness). The functions of time in (*b*) and (*d*) are a smooth step and a smooth pulse, respectively. When they multiply the field in (*a*) they generate the wave functions depicted in (*c*) and (*e*). The time corresponding to each frame is indicated by the shaded areas in (*b*) and (*d*). The step field enforces a persistent equilibrium position. The pulse field is a transient response that emulates the response to spinal stimulation shown in figure 2.



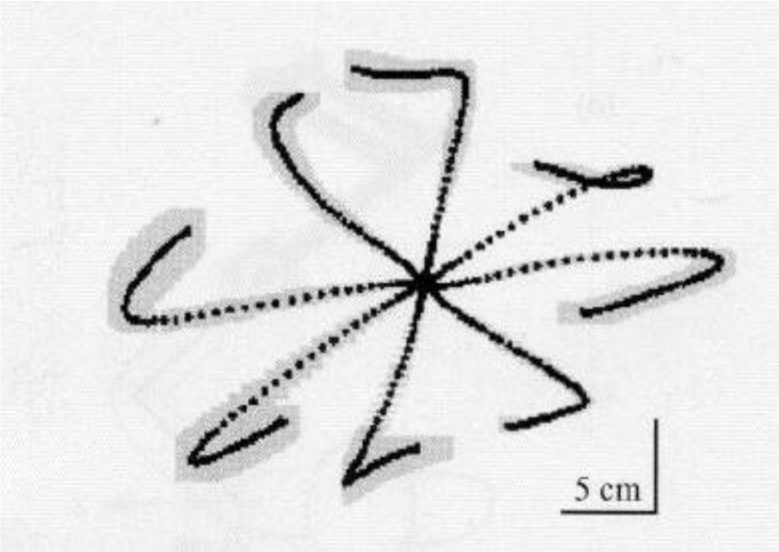
(a)
0.5
0
−0.5
−0.5
0
0.5
(b)
(c)
(d)
0.5
0.4
0.3
0.2
0.1
0
y (m)
−0.2
0
0.2
x (m)



(a)
y
x
10 cm
(b)
hand y-velocity (m s^-1)
1
0.5
0
−0.5
−1
−1 −0.5 0 0.5 1
hand x-velocity (m s^-1)
(c)
150
100
50
0
−50
−100
−150 −50 50 150
displacement (mm)
(d)
150
100
50
0
−50
−100
−150
−150 −50 50 150
displacement (mm)

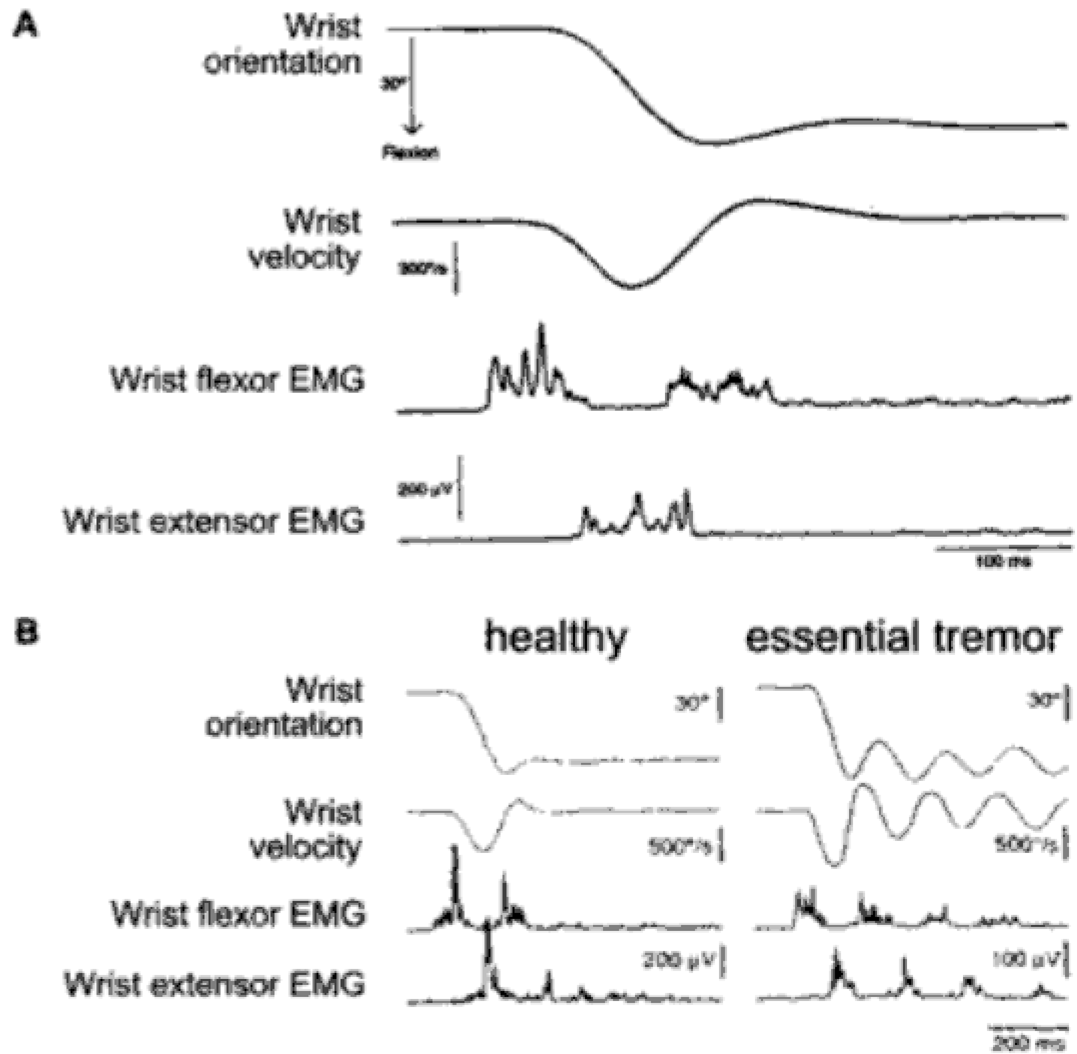


Adaptation, 250 trials per group



After effect

Example of EMG activity

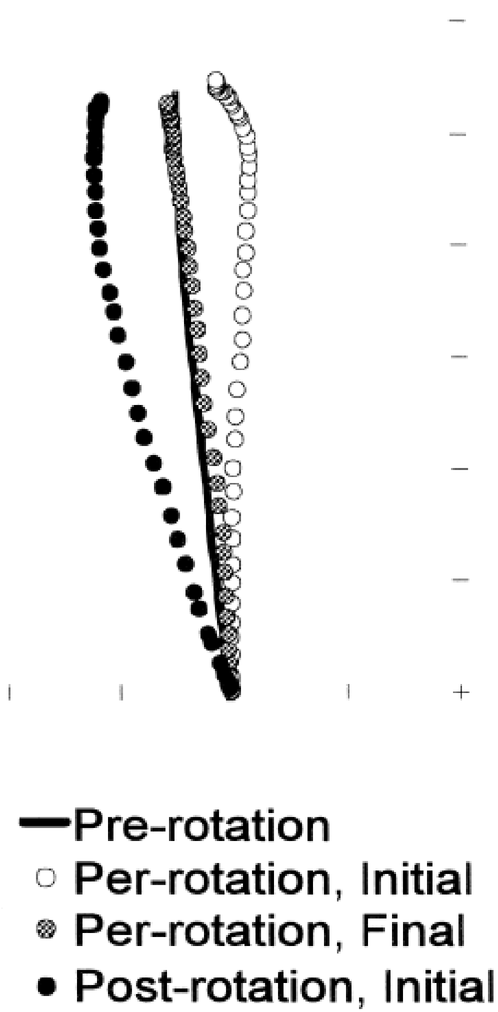


Equilibrium point hypothesis?

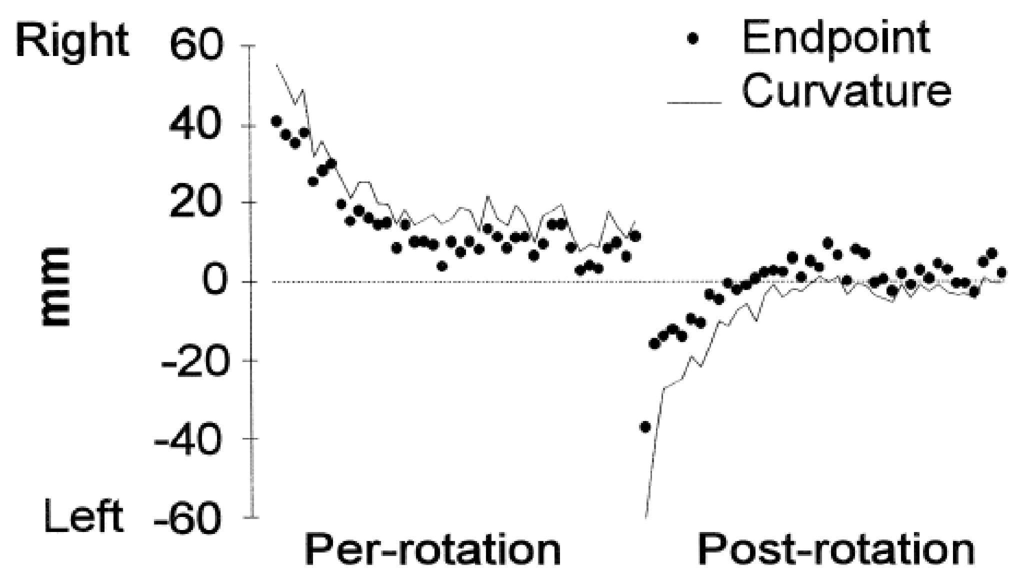
- Think of a changing activation as the movement of the equilibrium configuration of the limb
- Ok for slow movements, but what happens when moving fast
  - Dynamical effects
  - See the three-burst control
- Is there more?

Lackner & DiZio: internal model

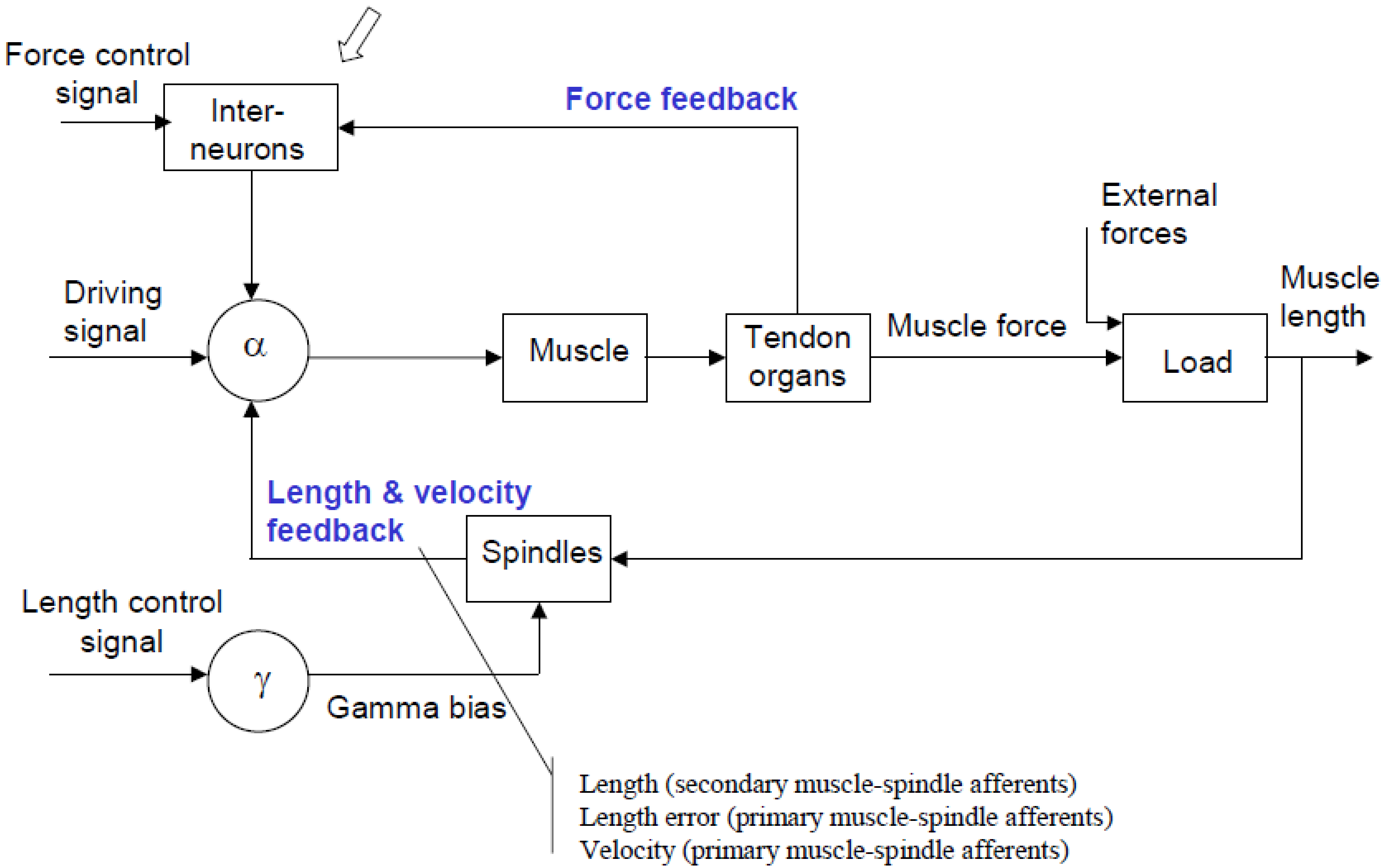
A

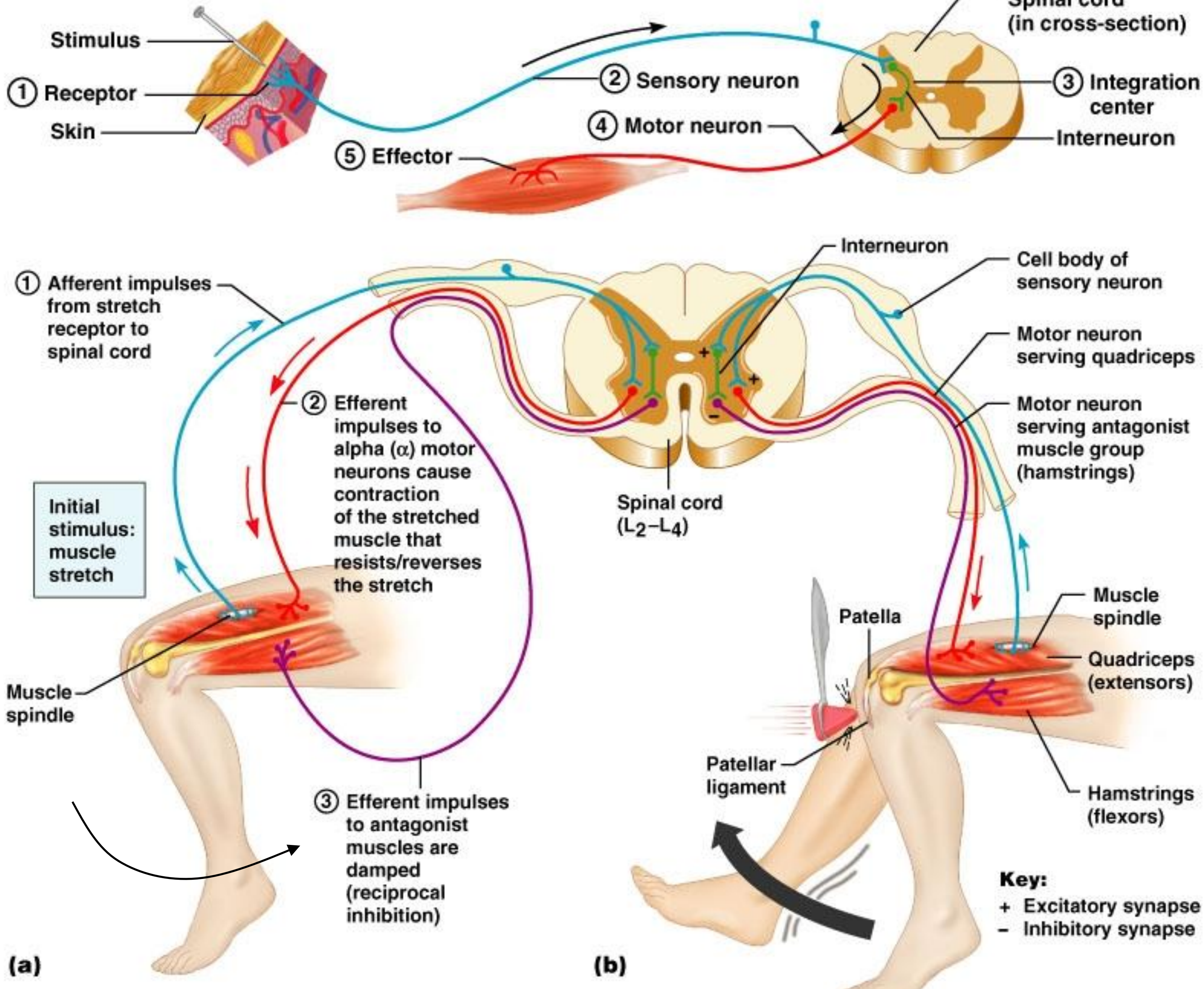


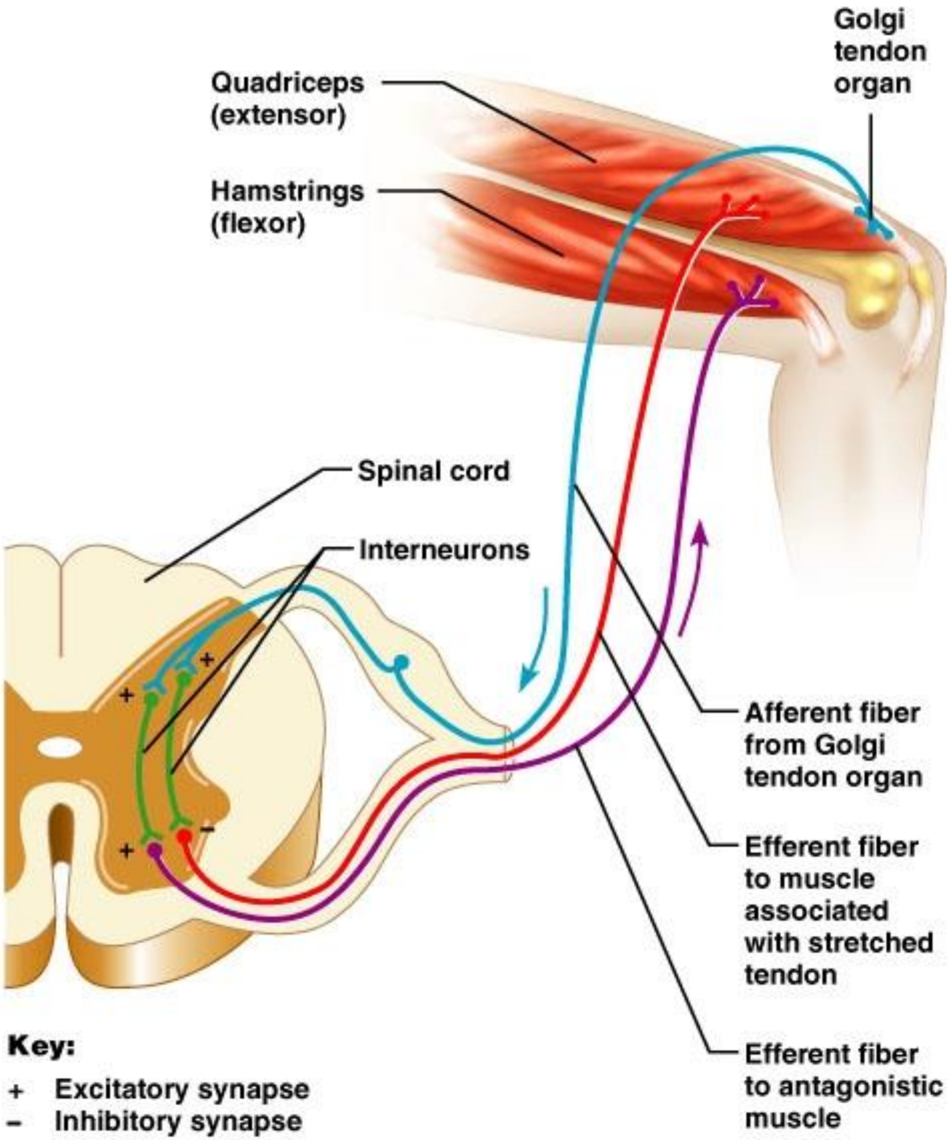
B



Spinal control (model)




Stimulus
① Receptor
Skin
② Sensory neuron
③ Integration center
④ Motor neuron
⑤ Effector
Spinal cord (in cross-section)
Interneuron
① Afferent impulses from stretch receptor to spinal cord
② Efferent impulses to alpha (α) motor neurons cause contraction of the stretched muscle that resists/reverses the stretch
Initial stimulus: muscle stretch
Muscle spindle
③ Efferent impulses to antagonist muscles are damped (reciprocal inhibition)
Interneuron
Cell body of sensory neuron
Motor neuron serving quadriceps
Motor neuron serving antagonist muscle group (hamstrings)
Spinal cord (L2–L4)
Patella
Muscle spindle
Quadriceps (extensors)
Patellar ligament
Hamstrings (flexors)
Key:
+ Excitatory synapse
– Inhibitory synapse
(a)
(b)


Golgi
tendon
organ
Quadriceps
(extensor)
Hamstrings
(flexor)
Spinal cord
Interneurons
+
+
+
+
–
Afferent fiber
from Golgi
tendon organ
Efferent fiber
to muscle
associated
with stretched
tendon
Efferent fiber
to antagonistic
muscle
Key:
+ Excitatory synapse
– Inhibitory synapse