The equilibrium point hypothesis reimagined: *Final position control*

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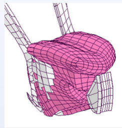
Alan A Wrench and Peter R Balch

@awrench

Queen Margaret University
CLINICAL AUDIOLOGY, SPEECH AND LANGUAGE RESEARCH CENTRE

Introduction

We are interested in modelling the articulation of the tongue at the neuromuscular level. We have built an interactive software platform for building 3D biomechanical models. We are pursuing the idea that saccadic eye movement, fast limb movement and lingual speech articulation share a similar neuromuscular control concept. We have built a simple 4-muscle 2-joint limb model to develop and test possible control concepts.



(Sin3D tongue model)

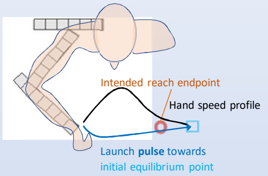
Proposal

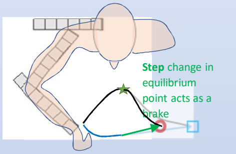
1. A reaching gesture consists of two volitional final position instructions,
   a) an initial launch **pulse** towards a distant equilibrium point that determines velocity and initial direction

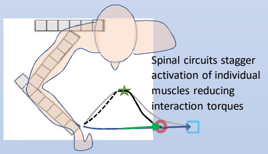
   optionally followed by another pulse or

   b) a landing **step** defining the resting target equilibrium point
2. Spinal interneurons stagger the activation of individual muscles, reducing joint interaction torques, jerk, and in doing so, straighten the trajectory of the launch pulse.
3. Timing of the pulse-step transition is controlled to avoid undershoot or overshoot.
4. Curved trajectories occur when launch pulse direction differs from target direction.

Proposals 1 & 2 are investigated here.



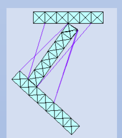


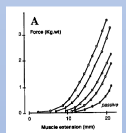


Method

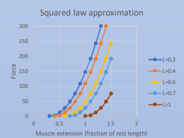
Biomechanical simulation is based on muscle motoneurons having descending excitation with Ia afferent excitation . λ sets descending excitation level (= nominal muscle length with no load). Afferent Ia stretch feedback (l+Δl) of muscle length (l) and stretch speed (Δl) provide reflexive excitation.

where force = $(l + \Delta l - \lambda)^2$ $\quad l + \Delta l > \lambda \quad$ force = 0 for $l + \Delta l <= \lambda$





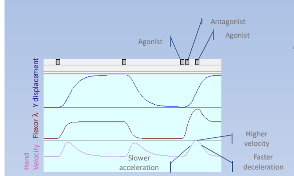
Force-length curves for different voltages (0V,2V,3V,4.5V) of 70Hz square wave (0.1ms pulse duration) of the cerebellar nucleus (cat) i.e. different levels of motor command activity. (Feldman and Orlovsky,1972)

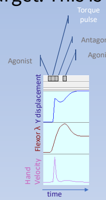


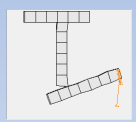
$$F = k * (\Delta l)^2$$

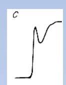
Single joint simulation results

Force arm to target and release just after reach is initiated -> arm moving back towards start position before reaching target. This is due to staggered muscle activation.





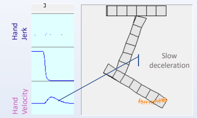




Angular displacement from Bizzi et al 1884

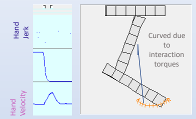
Two joint simulation results

(1). Reach – single equilibrium point (EP) at target (i.e. pulse EP = Step EP)



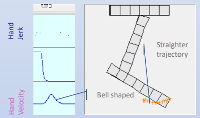
(2). Reach – pulse to EP beyond target followed by step to EP at target Joint interaction torques so - target reached via curved path with jerk.

Note : Higher peak velocity and faster deceleration



(3) Same pulse step EP as (2) but staggered activation of each muscle (generated manually by trial and error)

Target reached by straighter path, reduced jerk and bell shaped velocity profile.



Note1: Pattern of muscle delays needed for straight path matches phasic EMG pattern
Note2: Muscle activation order depends on direction.
Note3: Movement velocity control does not require increased stiffness

Discussion

Simulation indicates that a reach can be broken down into an initial pulsed launch towards the target followed by a corrective step to land on the target. The initial pulse generate higher interaction torques which can be mitigated by staging of activation of neuromuscular components of that command. In these simulations the λ commands are staggered as we have not yet developed a spinal network for this purpose.

Conclusion

The single joint simulation is compatible with the result of Bizzi et al 1984. Simulation of single joint and two joint pulse step EP control (i.e. two stage final position control) has not disproved the concept.

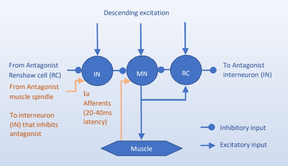
REFS

BIZZI, E., ACCORNERO, N., CHAPPLE, W. and HOGAN, N., 1984. Posture control and trajectory formation during arm movement. Journal of Neuroscience, 4(11), pp. 2738-2744.

Future

We are currently investigating a model based on selection and timing of 2 final position equilibrium points where dynamics of interaction torques are regulated by spinal interneuron circuits. **Buhrmann & Di Paolo (2014)** describe a similar model where "tuned" spinal circuitry compensates for interaction torques. Their model adheres to EPH tenets where central commands comprise of monotonic shifts in equilibrium point that control trajectory and the amount of co-contraction of agonist antagonist pairs controls velocity. **Tsianos & Loeb (2014)** also describe a spinal circuit model. They train their interneuron network using a cost minimisation based on squared deviation from kinematic target and energy consumed by each muscle. It resulted in phasic muscle activity and straight paths.

Barto,Fagg,Sitkov & Houk (1999) proposed a pulse-step EP model but damping in their model prevented Equilibrium point targets being reached.

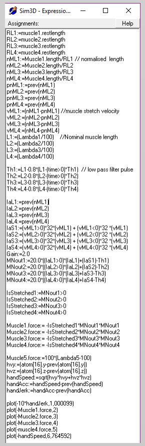


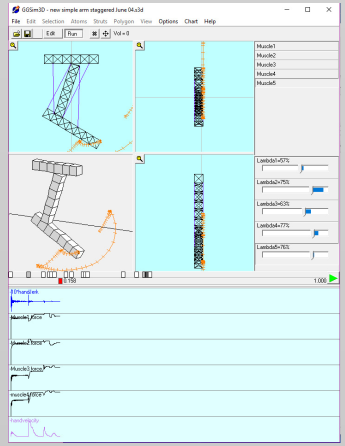
Simple Ia spinal circuit

We are attempting to determine how the spinal network generates the phasic response.

Supplementary Data

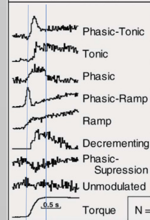
3D modelling environment





Neural response patterns during movement

E.E. Fetz et al. / Brain Research Reviews 40 (2002) 53–65



Response Type	CM	RM	DRG	PreM IN	Sy-IN	U-IN	MU
Phasic-Tonic	48%	46%	21%	36%	23%	35%	22%
Tonic	28	8	52	33	53	39	41
Phasic	2	20	27	14	13	17	4
Phasic-Ramp	10	0	0	2	0	1	0
Ramp	6	0	0	1	3	1	0
Decrementing	5	3	0	4	0	5	33
Phasic-Supression	0	0	0	7	0	3	0
Unmodulated	0	23	0	3	7	–	0
Torque (0.5 s) N =	211	61	29	100	30	433	114

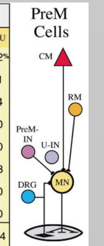


Fig. 3. Summary of response patterns in the preferred direction for different populations of neurons during generation of flexion and extension torques at the wrist. Examples of each pattern are illustrated on the left, and schematic of populations on the right. Proportions are given for corticomotoneuronal (CM) [7,8] and rubromotoneuronal cells (RM) [29], premotor afferents in dorsal root ganglia (DRG) [14], spinal premotor interneurons (PreM-IN), spinal unidentified interneurons (U-IN), spinal interneurons with synchrony effects (Sy-IN) and motoneurons (MU; combined data from motor units [35] and motoneurons [27]). Unmodulated U-INs are not included because their proportion could be made arbitrarily large.

Cerebellum–based positional error correction