Development of Complex Curricula for Molecular Bionics and Infobionics Programs within a consortial* framework**

Consortium leader

PETER PAZMANY CATHOLIC UNIVERSITY

Consortium members

SEMMELWEIS UNIVERSITY, DIALOG CAMPUS PUBLISHER

The Project has been realised with the support of the European Union and has been co-financed by the European Social Fund ***

**Molekuláris bionika és Infobionika Szakok tananyagának komplex fejlesztése konzorciumi keretben

***A projekt az Európai Unió támogatásával, az Európai Szociális Alap társfinanszírozásával valósul meg.

Neuromorph Movement Control

Neuromorf mozgás szabályozás

Optimization techniques in motor control

(Optimalzációs technikák a motoros vezérlésben)

József LACZKÓ PhD; Róbert TIBOLD

Main points of the lecture

- **Optimization of smoothness in workspce and in joint space.**
- **Partitioning of endpoint jerk.**
- **Examples for angular jerk.**
- **Optimazation of energy,**
- **Optimization of change of torque**
- **The least square solution**
- **Minimizing performance indices**
- **Equlibrium point hyphothesis**

Motor redundancy and motor overdeterminancy

Determined sets of equations have as many equations as many unknowns they have. Equations derived from human movement studies are rarely determined.

Underdetermined sets of equations have more unknown than equations and they have many solutions.
Such equation systems can give a particular solution only if additional criterias, restrictions are added.

Optimization criteria helps us to find particular solutions.
The question is what kind of optimization criteria are satisfied by natural solutions of equation systems based on human motor tasks?

Minimization of movements

- **In lecture 6. the synergy issue was investigated. The multi-joint musculosketal structures has more components than absolutely necessary to execute a motor task. The elements of the systems must work together to find a "good" solution.**

- **„What is stabilized by the central nervous system (CNS)?"**
- **What are the variables used by the CNS to control voluntary movements?**

Parameters that can be controled:

- Endpoint position (jerk, trajectory)
- Joint rotation (jerk,torque)
- Execution time-speed
- Exerted muscle force

1. **Minimizing the jerk (minimum jerk model)**

   Jerk is the rate of change of acceleration.

   (derivative of acceleration)

   The jerk of the endpoint of the limb or the jerk of the angular changes in the joints are of interest.

   Thus jerk is the third time derivative of position (or angle),

2. **Minimizing the change of joint torques (minimum torque change model)**

Basic difference: the minimum jerk model consider only the kinematics, the minimum torque change model accounts movement dynamics

The minimum jerk model

- **The redundancy problem and multi-joint limb movements**

- **Redundancy:** the number of participating muscles and joints are higher than necessary to execute an intended movement and there are many combinations of muscle activities and joint rotations to execute the given motor task.
- One of the most commonly used method to solve the redundancy problem is to find the minimum jerk trajectory by minimizing:

$$I = \int_0^T \left(\frac{d^3 r}{dt^3} \right)^2 dt$$

- where ***r*** is the endpoint position as function of time.

The minimum jerk model

- **Due to the minimum jerk model:**
- The trajectory of the movement should be as smooth as possible
- **Given the following joint configuration vector:**

$$\alpha(t) = \left[\alpha_1(t) \quad \alpha_2(t) \quad \ldots \quad \alpha_n(t)\right]$$

(n-dimensional vector of joint angles where n is the number of joints)

- **It was presented:** the Jacobian represents the relation between the change of joint configuration and change of endpoint position.
- The velocity of the endpoint is calculated:

$$p'(t) = J(t)\alpha'(t)$$

- To solve the minimization criterion of the model the 2nd derivative of the velocity of the endpoint must be calculated

The minimum jerk model

- **Computing the 3rd derivatives of *p(t)*:** $p'(t) = J(t)\alpha'(t)$

$$p''(t) = (p'(t))' = (J(t)\alpha'(t))' = J'(t)\alpha'(t) + J(t)\alpha''(t)$$

$$p'''(t) = (p''(t))' = (J'(t)\alpha'(t) + J(t)\alpha''(t))' =$$
$$= J''(t)\alpha'(t) + J'(t)\alpha''(t) + J'(t)\alpha''(t) + J(t)\alpha'''(t) =$$
$$= J''(t)\alpha'(t) + 2J'(t)\alpha''(t) + J(t)\alpha'''(t)$$

- Where **J** is the Jacobian, **J'** and **J''** the derivatives of **J**,

α is the joint configuration vector

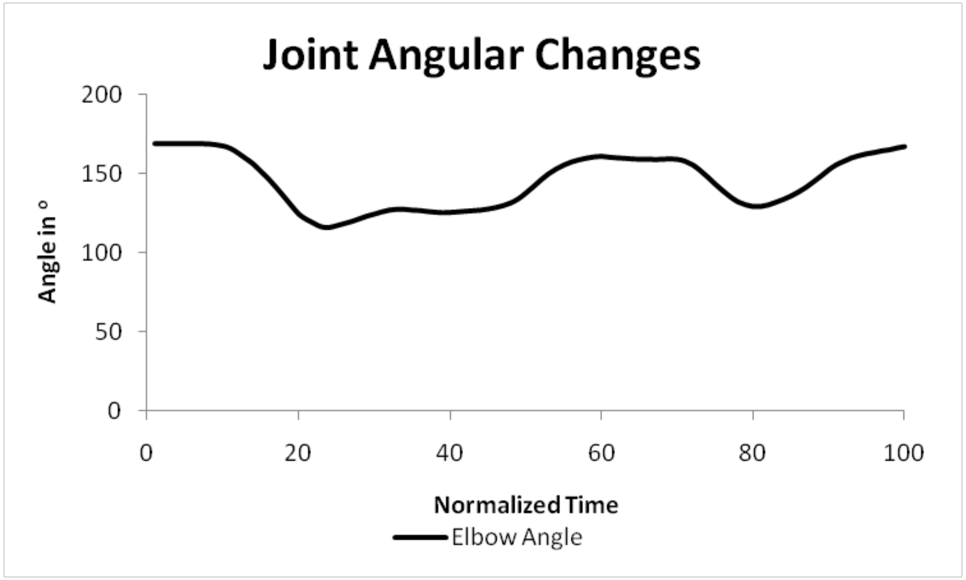
- The time derivatives of **α**:

$$\alpha'(t) = \begin{bmatrix} \alpha_1'(t) & \alpha_2'(t) & \alpha_3'(t) \end{bmatrix}$$

$$\alpha''(t) = \begin{bmatrix} \alpha_1''(t) & \alpha_2''(t) & \alpha_3''(t) \end{bmatrix}$$

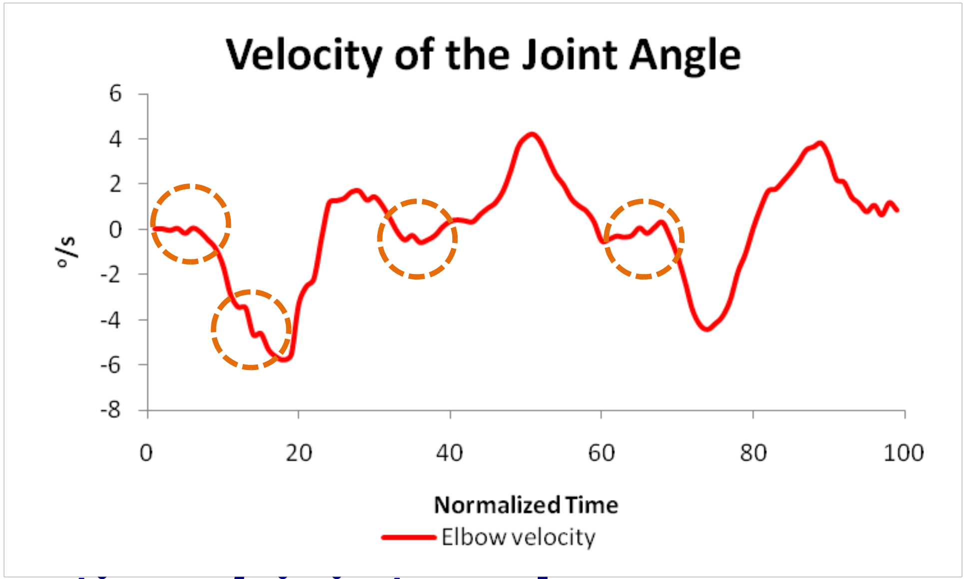
$$\alpha'''(t) = \begin{bmatrix} \alpha_1'''(t) & \alpha_2'''(t) & \alpha_3'''(t) \end{bmatrix}$$

The minimum jerk model – Data processing (handling of time derivatives)



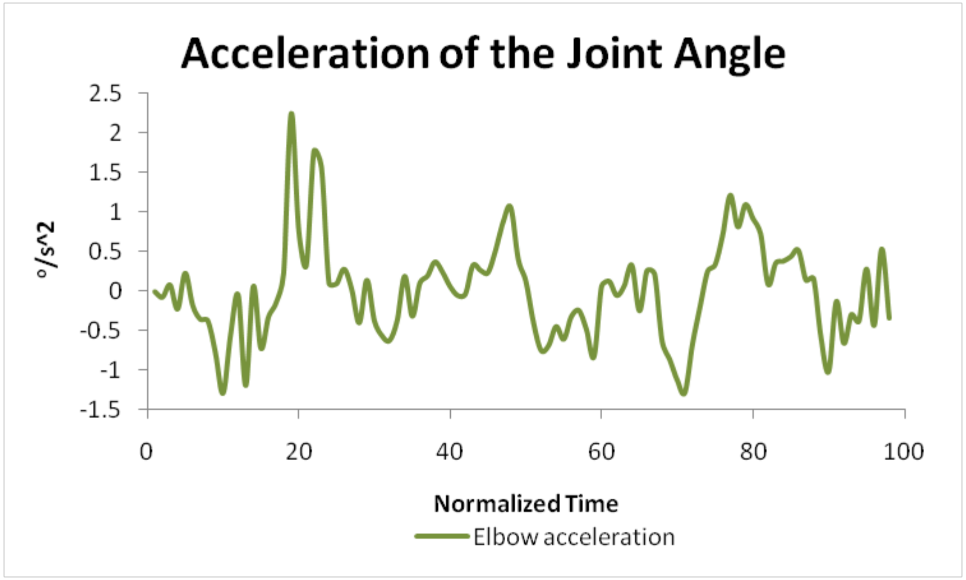
- **Joint angular changes**

The minimum jerk model – Data processing (handling of time derivatives)



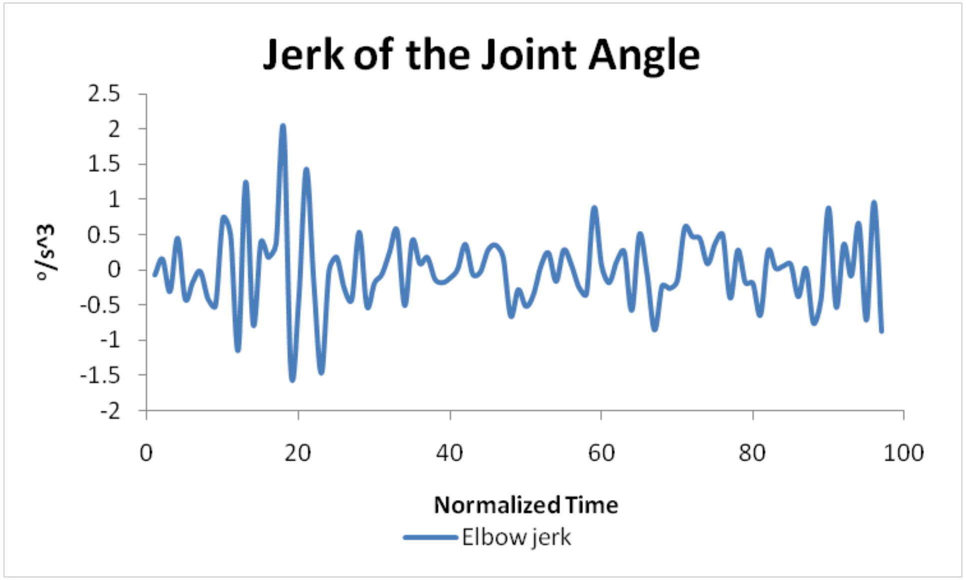
- **1st time derivative of joint angle**
- **Noise ( ) is increasing with time derivatives**
- **Methods reducing noise: RMS, moving avarage**

The minimum jerk model – Data processing (handling of time derivatives)



- **2nd time drivatives of the joint angle presented in the previous slide (increasing noise)**
- **Methods reducing noise: RMS, moving avarage**

The minimum jerk model – Data processing (handling of time derivatives)



- **3rd time drivatives of the joint angle presented in the previous slide (increasing noise)**
- **Methods reducing noise: RMS, moving avarage**

The minimum jerk model – Integral measures of the endpoint jerk)

- **The underlying principle (integral of the square of 3rd derivative of the endpoint position over movement time)**

$$I = \int_0^T \left(\frac{d^3 r}{dt^3} \right)^2 dt$$

Can be decomposed into these terms:

$$\int |g(t)|^2 dt = \int |g_1(t)|^2 dt + \int |g_2(t)|^2 dt + \int |g_3(t)|^2 dt + 2\int (\langle g_1(t), g_2(t) \rangle$$
$$+ \langle g_1(t), g_3(t) \rangle + \langle g_2(t), g_3(t) \rangle) dt$$

- ♦ **denotes a scalar product of vectors:**
- ♦ **G3 is the dominant of three terms**

$$g_1(t) = J''(t)\alpha'(t)$$
$$g_2(t) = 2J'(t)\alpha''(t)$$
$$g_3(t) = J(t)\alpha'''(t)$$

The minimum jerk model

- **Within all possible trajectories we have to choose the smoothest one by minimizing:**

$$C = \frac{1}{2}\int_0^{t_f}\left(\left(\frac{d^3x}{dt^3}\right)^2 + \left(\frac{d^3y}{dt^3}\right)^2 + \left(\frac{d^3z}{dt^3}\right)^2\right)dt$$

- **After minimizing this integral: (jerk computation and summation) the minimum jerk trajectory will be a straight line and the velocity and accelartion profiles will depend on the initial and final velocity and accelaration of the enpoint of the limb (boundary conditions).**
- **An example is given on the following slide for zero initial and final velocity and acceleration.**

This is a problem of variational calculus.

We assume that the following boundary criteria are given:

P'(0) =0, P'(T)=0

P''(0)=0, P''(T)=0

(T is total movement time, P(t)=(x(t),y(t),z(t))),

Than the following (x(t),y(t),z(t)) function minimizes the C functional given on the previous slide

$$x(\tau) = x_0 + (x_0 - x_T)(15\tau^4 - 6\tau^5 - 10\tau^3)$$
$$y(\tau) = y_0 + (y_0 - y_T)(15\tau^4 - 6\tau^5 - 10\tau^3)$$
$$z(\tau) = z_0 + (z_0 - z_T)(15\tau^4 - 6\tau^5 - 10\tau^3)$$

The minimum torque-change model for multi-joint movements

The following cost function should be minimized:

$$E = \int_0^T \sum_i^n \frac{dMi(t)}{dt}^2 dt$$

M_i is the torque (moment) in the i^{th} joint,
T is movement time, n is the number of joints

The movement time must be known in advance by the controller.
While the minimum jerk modely is purely kinematical, the minimum torque-change model takes into account movementdynamics

The least square solution

If a displacement of the endpoint of an n-joint system is represented in the n-dimensional joint space than the least square solution gives that displacement that is the shortest one in joint space.

Here distance is based on a Euclidean norm of the joint space.

The least square solution gives that displacement for which the sum of the squares of the angular changes in the joints is minimal. (The length of the displacement in the joint space is minimal)

Physically this relates to minimizing rotational energy:

If the weighted sum of the squares of the angular changes is minimized assuming that the weights are the moment of inertias of the rotated body parts than the total **rotational energy** is minimized.

Minimizing rotational energy for multi-joint movements. The following cost function should be minimized:

$$E = \int_0^T \sum_i^n \theta i(t)\,\omega_i^2(t)\,dt$$

ω_i is the angular velocity in the i^{th} joint,
θi is the moment of inertia of the body part rotated around the i^{th} joint,
T is movement time, n is the number of joints

This is a very reasonable optimization criteria form a physical point of view. Note that to find the angular velocities that satisfy this criteria, the movement time must be known in advance by the controller.

The minimum torque-change model and the minimum rotational energy criteria involves dynamic factors of the system.

This makes them attractive. Although it is very difficult to apply them in certain particular cases because accurate information about the dynamic parameters must be known.

(E.g. moment of inertia)

Moment of inertia is also changing in time since one rotation in a joint usually rotates a bunch of body segments that may also rotating around each other.

Joint torque is a result of tensions of flexor and extensor muscles and the stiffness of these muscles are playing a direct role in generating torque.

The minimum jerk model predicts trajectories of point to point movements.

Comparing the minimum jerk and minimal torque-change models, the latter one corresponds better to actual data if the task is to move the limb's endpoint through an intermediate point that is not on the line of the initial and target position.

Velocity profiles of the endpoint of the limb is very similar for the minimum jerk and minimum energy criteria.

It is a question that whic optimization criteria are more „physiological" those which are based on endpoint positions or those which are based on joint angles?

We have seen that many optimization criteria were studied. These models yielded movement patterns that were supported by experimental data.

Sometimes it is diffcult to dstinguish berween movement trajectories that are derived from different optimization criteria.

Models for optimizing metabolic energy has also been developed.

The question is still open: can these optimization criterias satisfied with human bodz controlled bz brain and spinal structures?

Whatever above mentioned criteria is considered, „the rate of change of a controlled variable in the motor control system is limited" (Latash 1993)

Minimizing other performance indices

- Minimizing impulses
- I = mv (impulse is the product of mass and velocity)

According to Newton's second law F= dI/dt,

Thus impulse is the integral of force over time.

If a human movement is executed as fast as possible, than the solution with minimal impulse gives the minimal time solution.

The minimal impulse solution relates to the minimal peak velocity, assuming that the mass is constant during the movement. This is the case for human movements. If the peak velocity is minimzed than the acceleration during movement excution is minimzed wich means that muscle forces and ultimately underlying neural activity is minimized

Equlibrium point hyphothesis

For a given neural command the muscle length changes until the muscle force and an external perturbation or load are balanced.

If the load chages than the treshold of the strech reflex (λ) is changed by the central neural command to reach a new equilibrium.

The treshold defined by the central command to the muscle relates to the muscle length at which α motoneurons are activated in response to muscle length change.

λ is considered as a measure of depolarozation of the α motoneuron membrane for the motoneuron pool sending signals to the muscle (Feldman 1986)

A change in λ can imply a muscle length change even if the muscle force is constant or a muscle force change while muscle length is constant (Latash 1998)

Equilibrium trajectory hyphothesis

Extension of the equlibrium point hyphothesis from single muscles to multijoint systems.

The CNS performs a passive simulation of a virtual trajectory of a passive movement of the endpoint of the system from one point to another one. This trajectory is defined by minimizing **potential energy**.

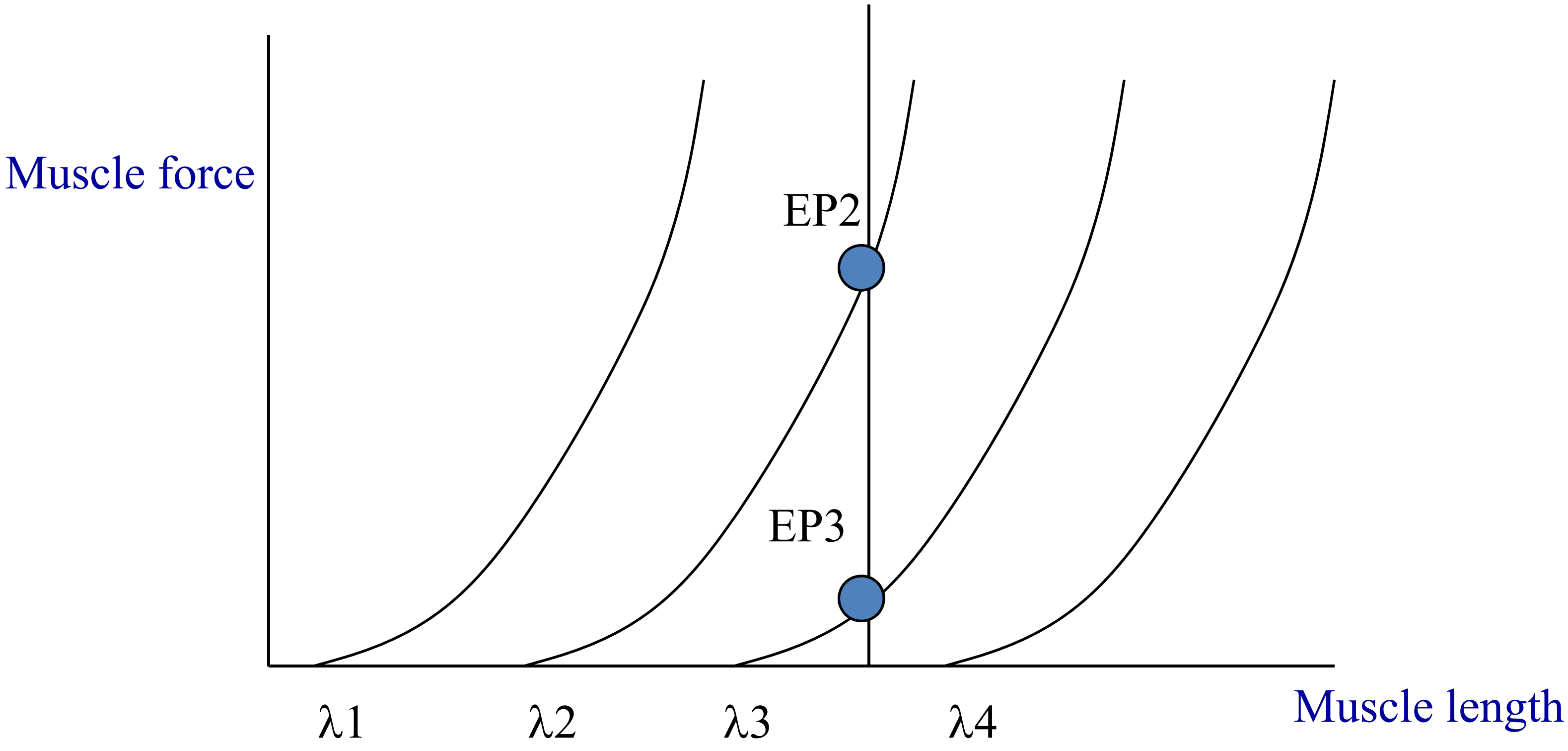
Then neural signals may adjust elastic muscle properties on that way that the movement will be performed as it was simulated inside CNS.

This can be applied for point to point (reaching) movements.

During target tracking (e.g. drawing) movement when a desired trajectory or is given by external (e.g. visual) stimuli.

According to the equilibrium trajectory hypothesis the central command is able to shift an internal image of the working point along a desired trajectory expressed in external coordinate systems

Equilibrium point hyphothesis



The central command may change muscle force without changing muscle length by changing λ

The central command may change the threshold (λ) of the tonic stretch reflex,

As a consequence the whole force-length characteristic is shifted.

The curve of the force-length relation is invariant, it can not be changed by the central command, only the threshold of the tonic stretch reflex can be changed to control movements

The threshold of tonic stretch reflex:

The muscle length at which autogenic recruitment of α motoneurons starts firing during a muscle stretch.

L is the point of deviation of the active and passive force-length characteristic of the muscle (Latash 1993)

Motricity

The ability for biologically inspired active movements (Llinas 2005).

Prediction and motricity are basic properties required for the development of the central nervous system. Motricity takes place at the periphery (muscular system) and spinal level as well.

Feedforward command for active movements:
to apply feedforward control the CNS must know the current state of the musculoskeltal system and predict the desired state. The central pattern generator produces the required active movement to reach the desired state.

Motricity

Feedback control means that the controller **uses the signals received form the sensory system during movement execution**. This feedback signal modifies the central pattern.

The brain and the spinal cord does not compute anything like computers do with their embedded algorithms.
The CNS rather generates a predicted image of an event to react optimally if required or needed.

The joints, muscles and their abilities are inscribed in the geometry of the neuro-musculo-skelatal system when we were born and then we can adopt to the environment in which we grow up.

Summary

- **An intended motor task can be executed at an infinity of different ways by a multijoint system as a human limb.**

- **It was investigated how an optimal solution can be defined and employed by neural control.**

- **The minimal jerk and the minimal torque change optimization criteria has been presented.**
- **The least square solution relates to optimization of rotational energy.**

- **The equilibrium point hypothesis for muscles and its generalization the equilibrium trajectory hypothesis for multijoint movements were discussed. The latter one relates to minimization of potential energy.**

Suggested literature

- Latash ML (1993). Control of Human Movements. Chicago IL: Human Kinetics
- Enoka R. Neuromechanical basis of kinesiology. Champaign IL. Human Kinetics. 1988.
- Bizzi E, Mussa-Ivaldi FA, Giszter S. Computations underlying the execution of movement: a biological perspective. Science 1991;253:287-91.
- Feldman AG: Once more on the equlibrium point hyphothesis (λ model) for motor control. Journal of Motor Behavior 18. pp. 17-54

Suggested literature

- Laczko J, Jaric S, Tihanyi J, VM. Zatsiorsky & Mark L. Latash (2000) “Components of the End-Effector Jerk during Voluntary Arm Movements” Journal of Applied Biomechanics V.16. pp 14-26
- Enoka R. Neuromechanics of Human movement (2002), Champaign IL. Human Kinetics, ISBN: 0-7360-0251-0
- Laczkó J., Jaric S., Latash ML., Zatsiorsky VM. (1997): The relation between individual joint kinematics and the minimal jerk principle as applied to the hand during planar movements. Soc. Neurosci. Abstr. Vol 23, Part 2. p. 2089.

Suggested literature

- Hogan N, Flash T (1987) Moving gracefully: quantitative theories of motr coordination Trends in Neurosciences, Volume 10, Issue 4, pp,170-174
- Uno, Y., Kawato, M. and Suzuki, R., Formation and control of optimal trajectory in human multijoint arm movement. Minimum torque-change model, Biol Cybern, 61 (1989) 89-101.
- Wada Y., Kaneko Y., Nakano E., Kawato M.,(2001),Quantitative examinations for multi joint arm trajectory planning – using a robust calculation algorithm of the minimum commanded torque change trajectory Neural Networks, Volume 14, Issues 4-5, Pp: 381-393

Suggested literature

Llinas RR, (2001) I of the vortex: from neurons to self.
MIT Press, Cambridge MA 2001, ISBN 0-262-12233-2

Zatsiorsky VM, (1998) Kinematics of Human Motion, Publ, Human Kinetics, ISBN 0-88011-676-5

Zatsiorsky VM, (2002) Kintics of Human Motion, Publ, Human Kinetics, ISBN 0-7360-3778-0

Gomi H, Kawato M (1997): Human Arm Stiffness and equilibrium-point trajectory during multi-joint movement. Biological Cybernetics, 76. 163-171