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

**Consortium leader**

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**Consortium members**

# SEMMELWEIS UNIVERSITY, DIALOG CAMPUS PUBLISHER

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**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)**

# Synergies and redundancy of the motor system

**(A motoros rendszer szinergiája és redundanciája)**

**József LACZKÓ PhD; Róbert TIBOLD**

# Main points of the lecture

- **Synergy is investigated in this lecture**
  - **Muscle and joint synergy**
- **Computational method of variances for the endpoint of the limb and for joint configuration is also presented**
  - **For the upper and lower limb**
- **Synergy analysis is done by investigating the structure of variances (UCM analysis)**
  - **Total variance is decomposed to compensated and uncompensated variances**
- **Redundancy problem**

# The muscle and joint synergy

- **Synergy: the cooperation (collaboration) of individual parts of a system.**
- **Joint synergy:** The cooperation of joints in order to execute a motor task.
- **Muscle synergy:** The cooperation of muscles to execute desired joint rotations.
- The muscles may cooperate well, but if the nervous system is effected by certain disorders (Parkinson Disease, Stroke, …) then the cooperation is disturbed, the muscles do not work “together”

# Computation of variance in the endpoint and joint configuration

If the endpoint positions are noted by $p_k(t)$ and arm configurations with $a_k(t)$ where *k* is the serial number of the trial, and the means of these values across trials are $M_p(t)$ and $M_a(t)$, than the deviations of positions and arm configurations of the $k^{th}$ trial ($d_{kp}(t)$ and $d_{ka}(t)$) from its mean value are:

$$d_{ka}(t) = M_a(t) - a_k(t) \qquad d_{kp}(t) = M_p(t) - p_k(t)$$

Endpoint variance ($V_p(t)$) and arm configuration variance ($V_a(t)$):

$$V_a(t) = \frac{\sum_{k=1}^{n} d_{ka}(t)^2}{n-1} \qquad V_p(t) = \frac{\sum_{k=1}^{n} d_{kp}(t)^2}{n-1}$$

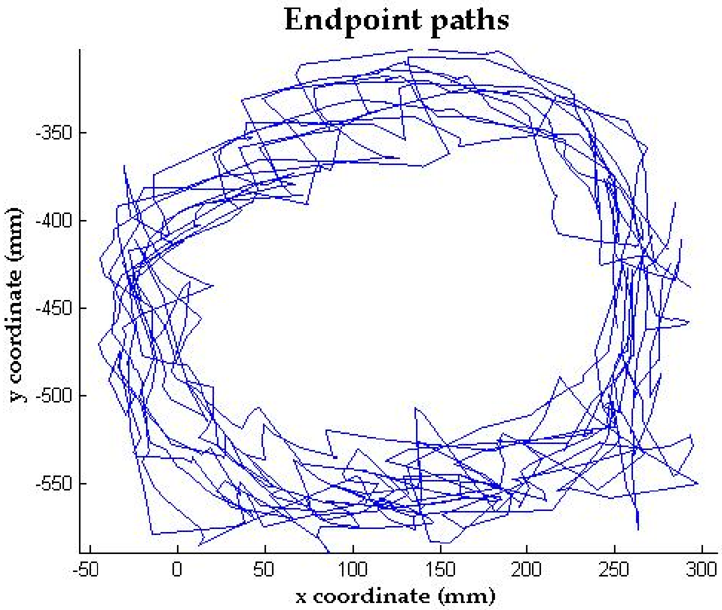
where the *n* is the number repetitively executed movements (trials).

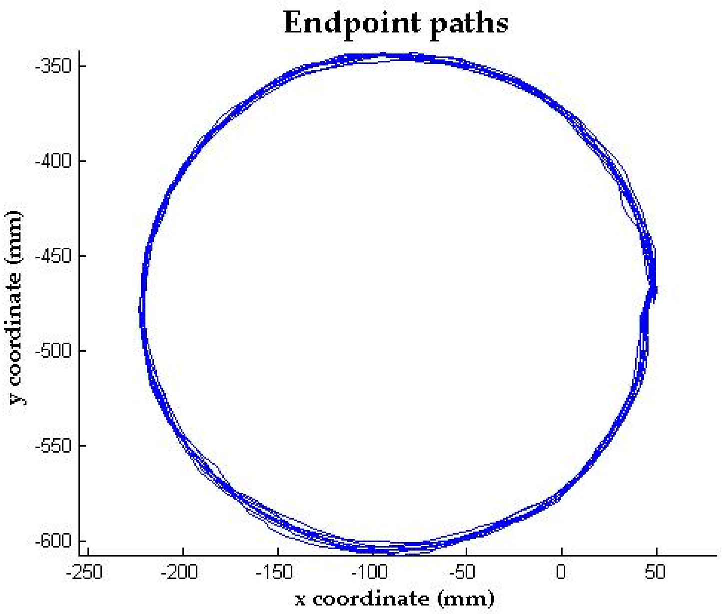
# Target tracking arm movements of healthy and stroke patients

- **The subjects saw a small moving disk on a computer display. They had to follow it with the mouse pointer on the screen controlled by an A/3 size digitizer tablet.**

- Two paths were applied(circle and rectangle) and two speed (normal and fast) parameters for the target.
- **During the movement:**
  - the **spatial (3D) position** of the subject's arm
  - **EMG activities** of Deltoid anterior, Deltoid posterior, Biceps and Triceps were recorded.

# Target tracking arm movements of healthy and stroke patients



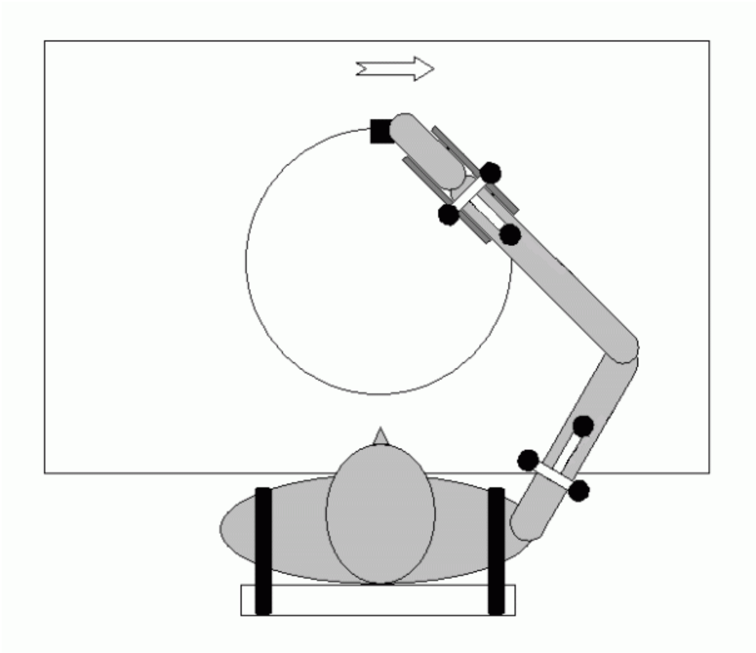



# Target tracking arm movements of healthy and Parkinsonian patients

**The subjects saw a given figure (circle, square)**

Subjects were asked to track (draw) the trajectory by moving a pen on a table.

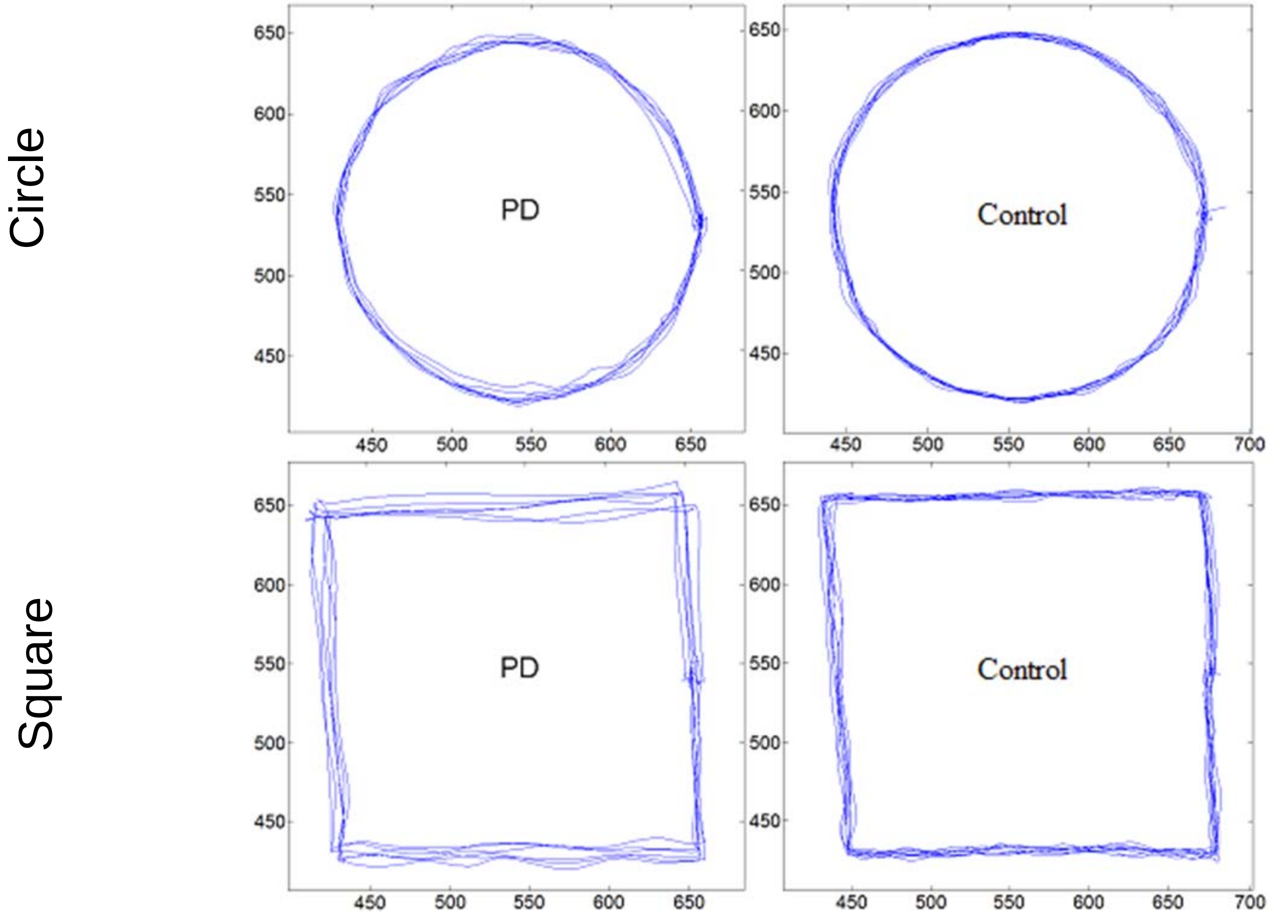
- Circle (diameter 23 cm)
- Square (length of the side 23 cm)
- Right hand
- Laft Hand



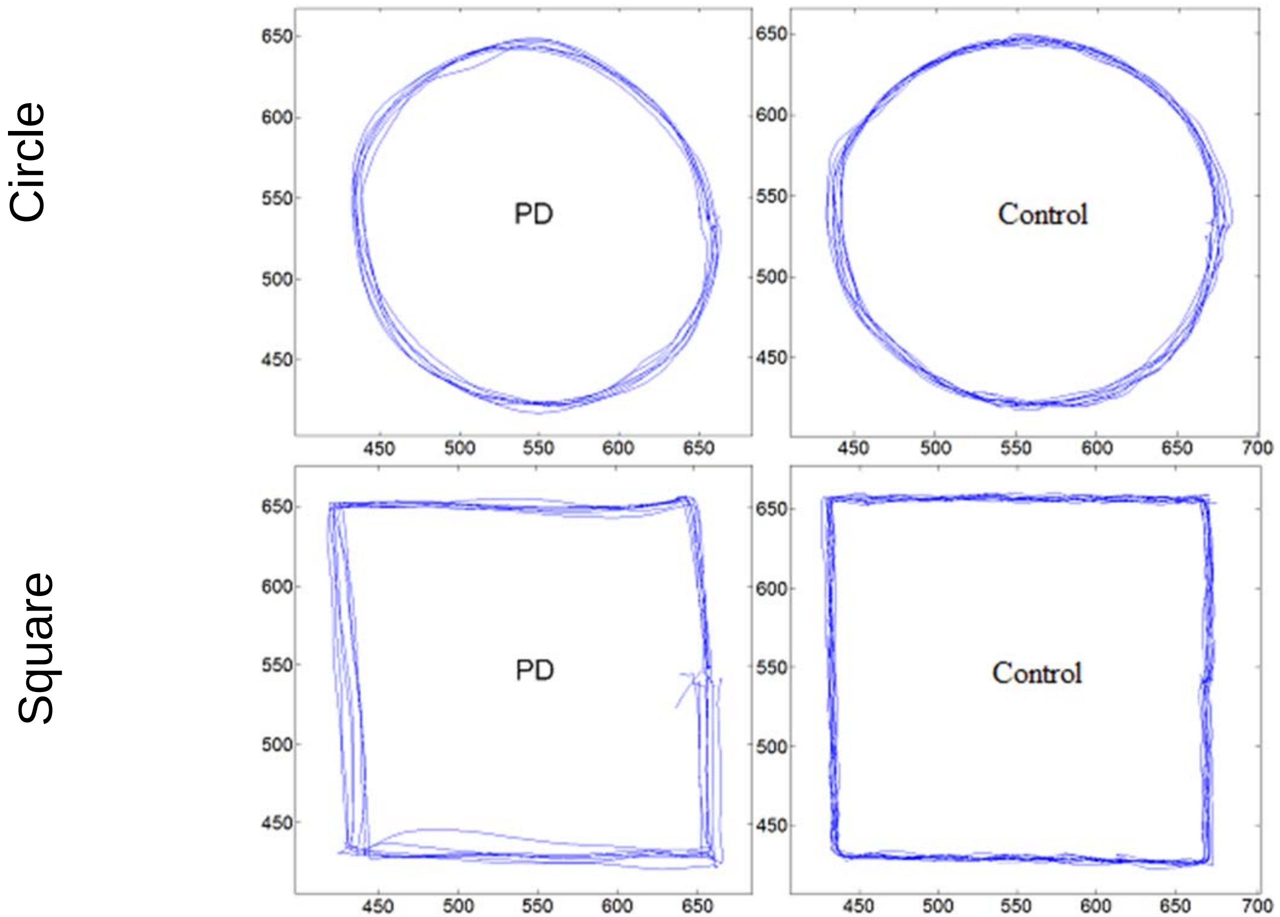
natural, confortable speed

7 drawings for each condition
(7 circle – 7 square)

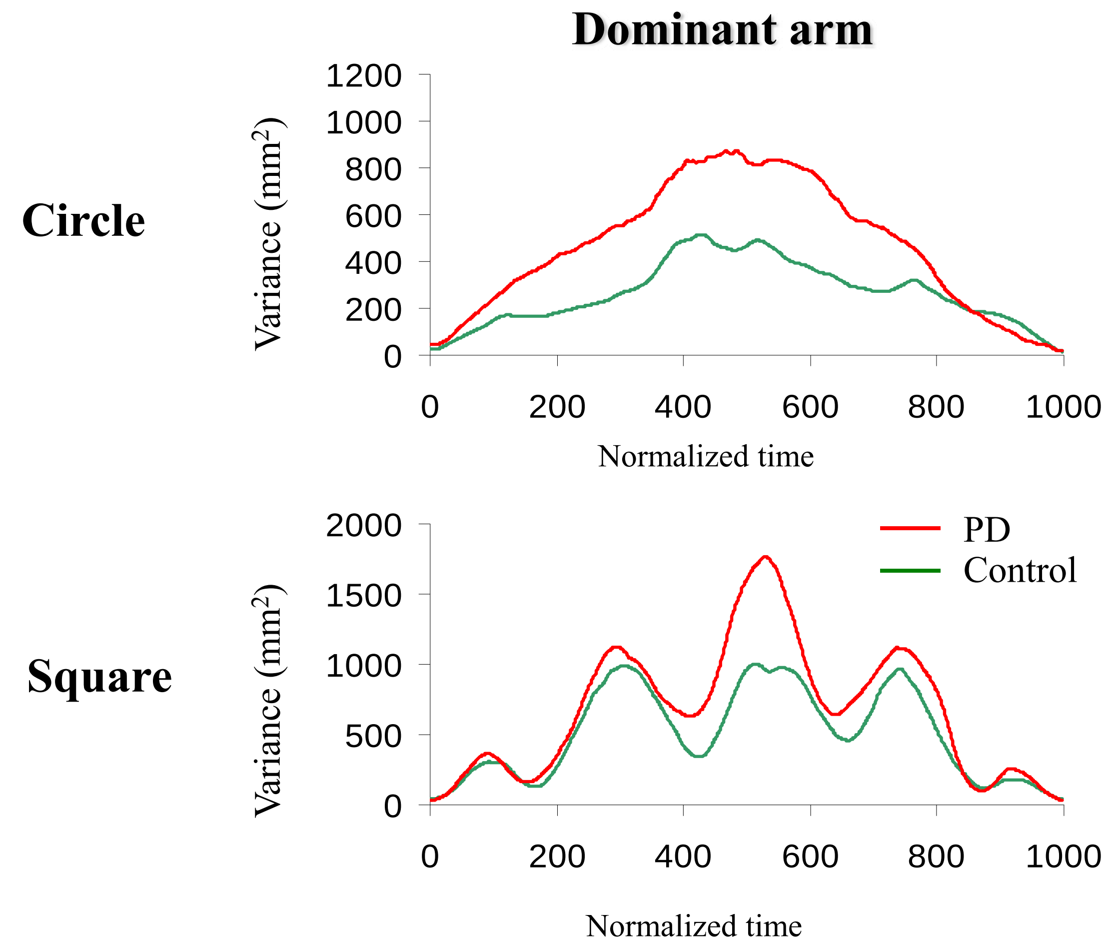
# Comparison of control and PD subjects – Trajectories (dominant hand)



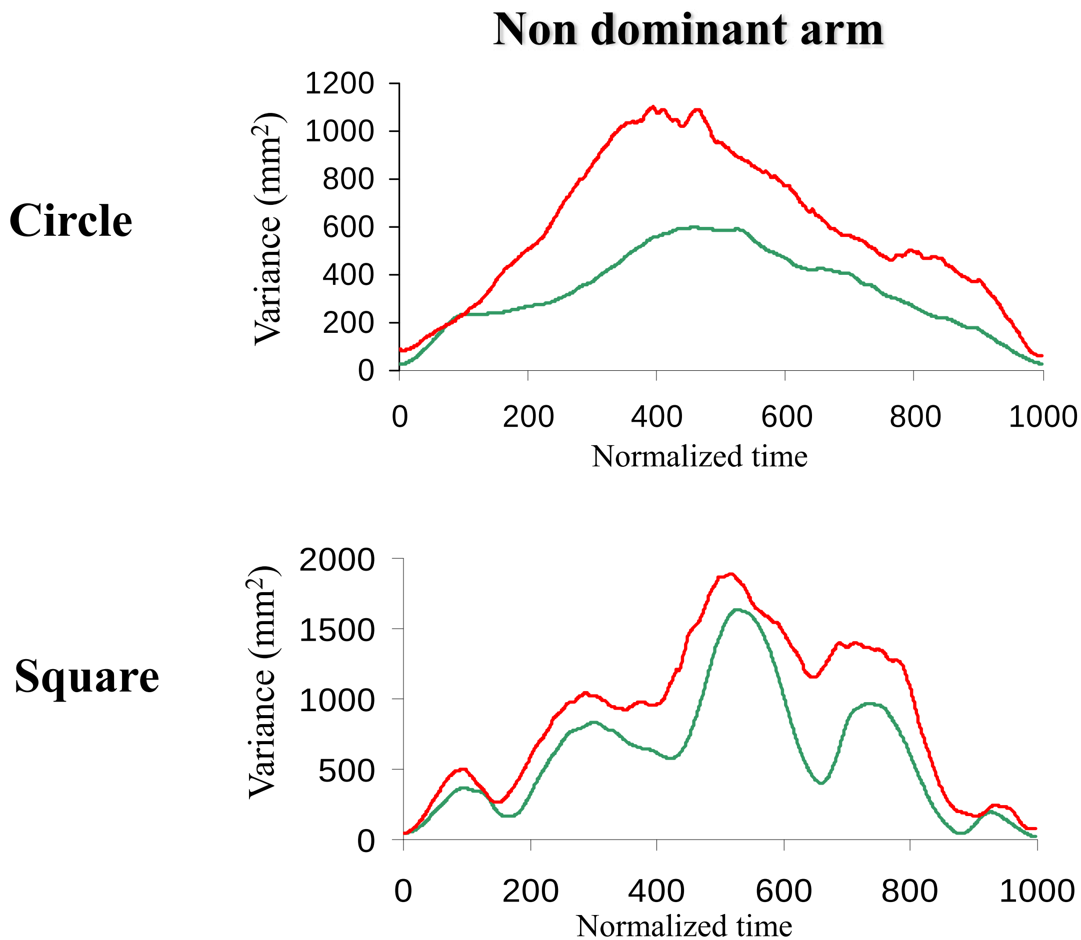
# Comparison of control and PD subjects – Trajectories (non-dominant hand)



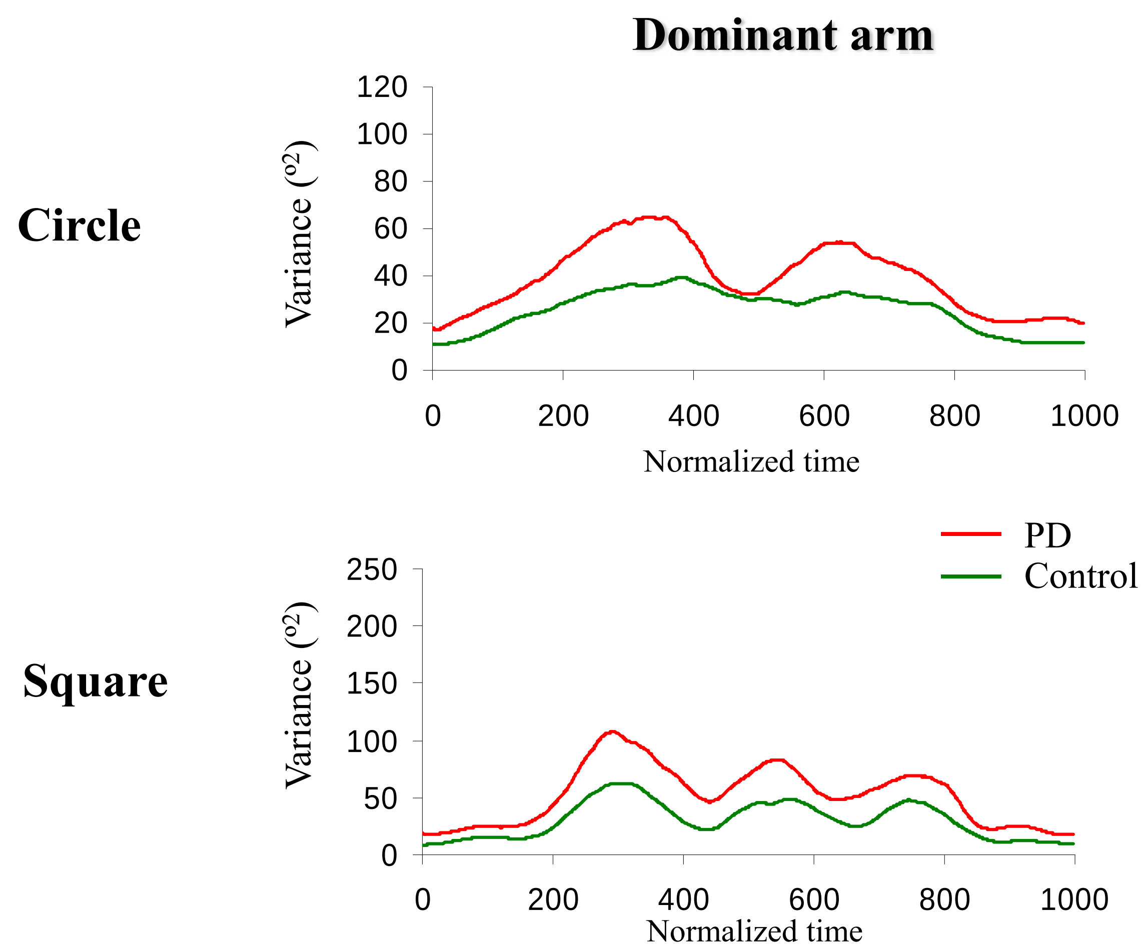
# Comparison of control and PD subjects – Endpoint variance



# Comparison of control and PD subjects – Endpoint variance



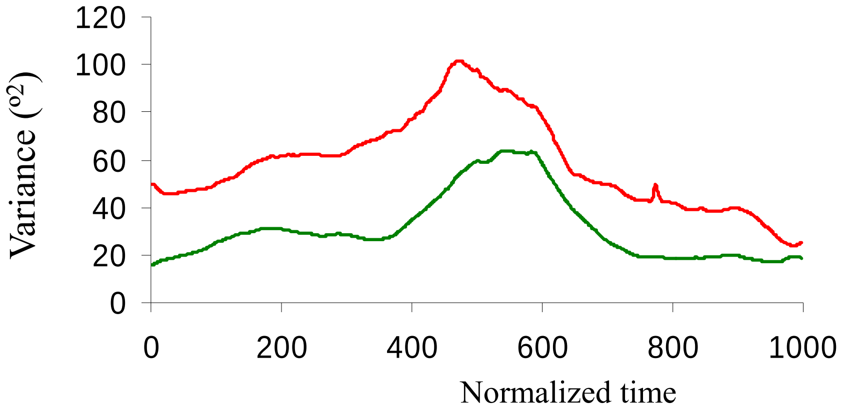
# Comparison of control and PD subjects – Joint configuration variance



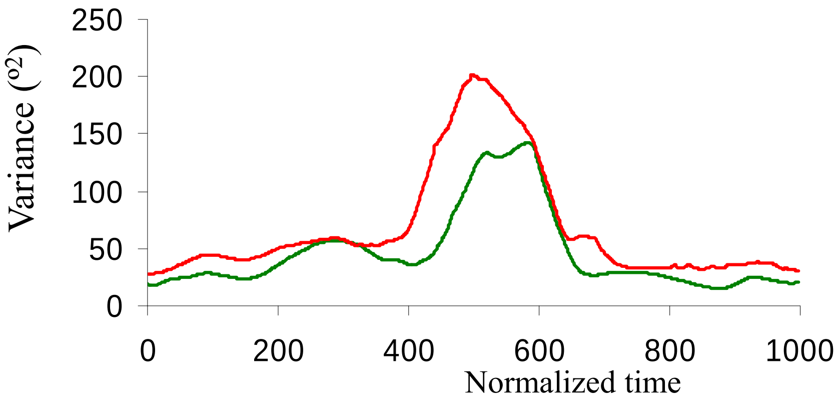
# Comparison of control and PD subjects – Joint configuration variance

## Non dominant arm

**Circle**




**Square**



# Moving the upper limb vertically with or without a load

**Healthy subjects sat in front of a 2-level-computer desk.**

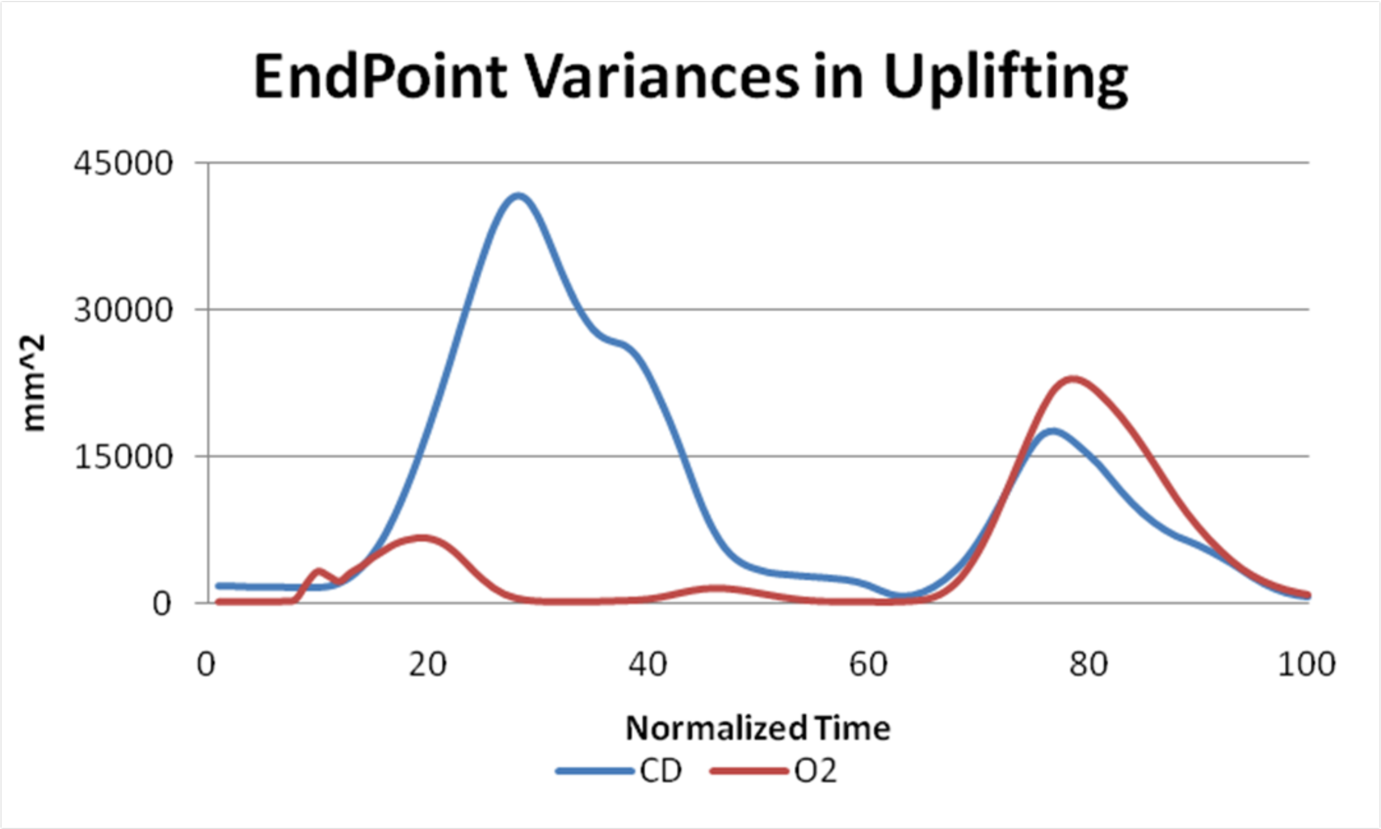
The motor task was executed under **two load conditions:**

- 1) CD case(0.06kg) [**CD**]
- 2) a load (2kg.) [**O2**]

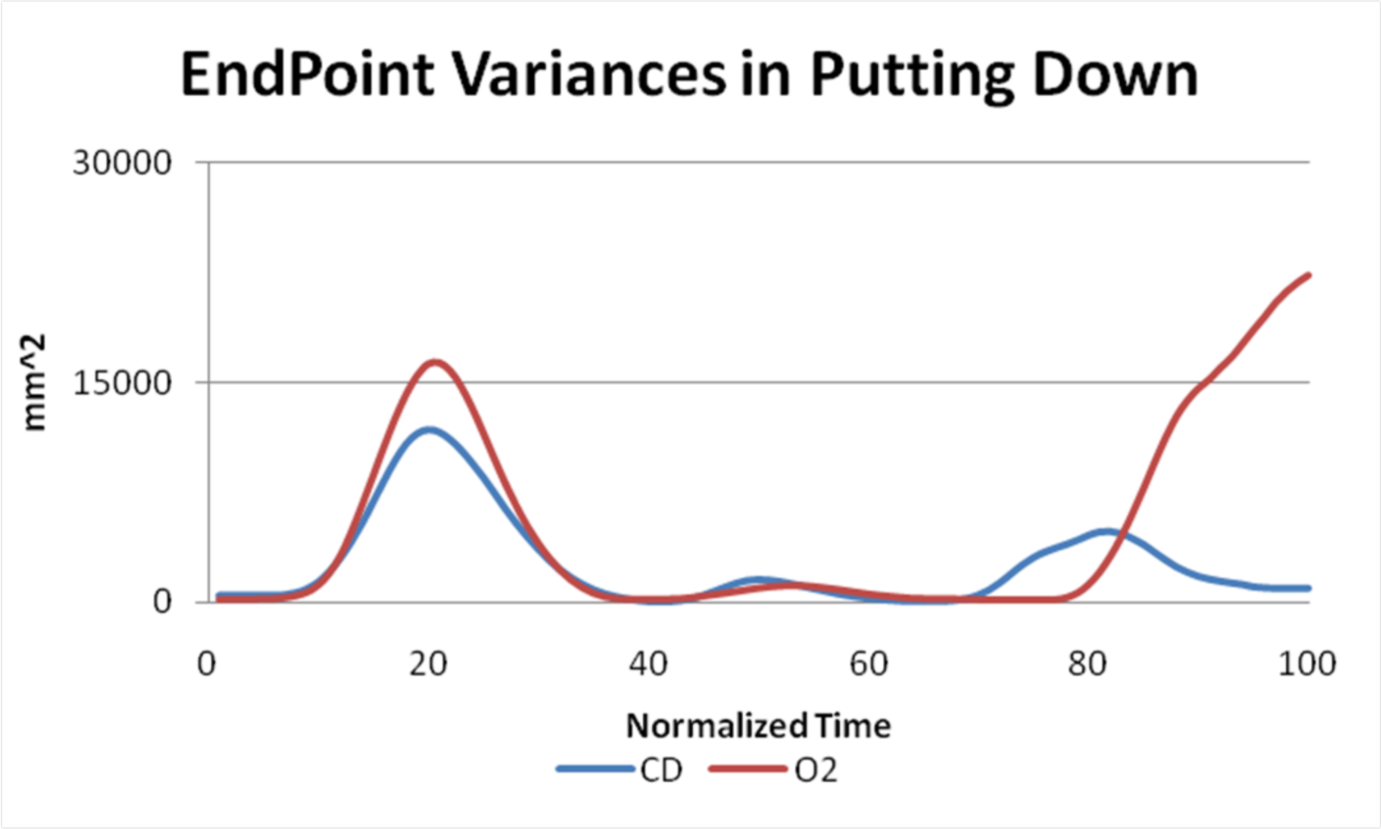
**uplifting:** the subject had to lift his arm to reach and grasp the object on the lower level of the desk and had to uplift it onto the upper level and finally put the arm back to the initial position

**putting down:** the subject had to lift his arm to reach the object on the upper level of the desk, put it back down to the lower level, release the object and move the arm back to the starting position.

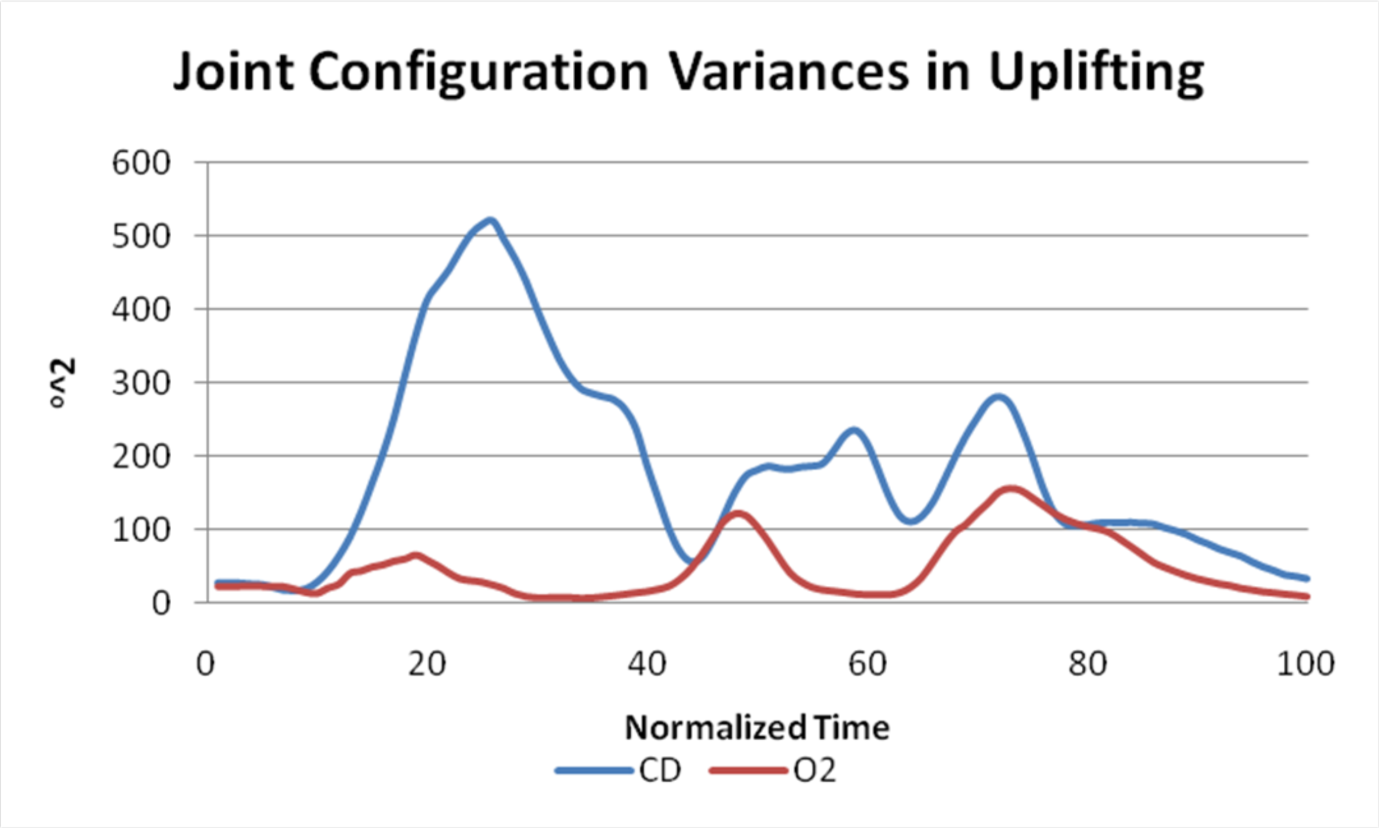
# Moving the upper limb vertically with or without a load (endpoint variances)



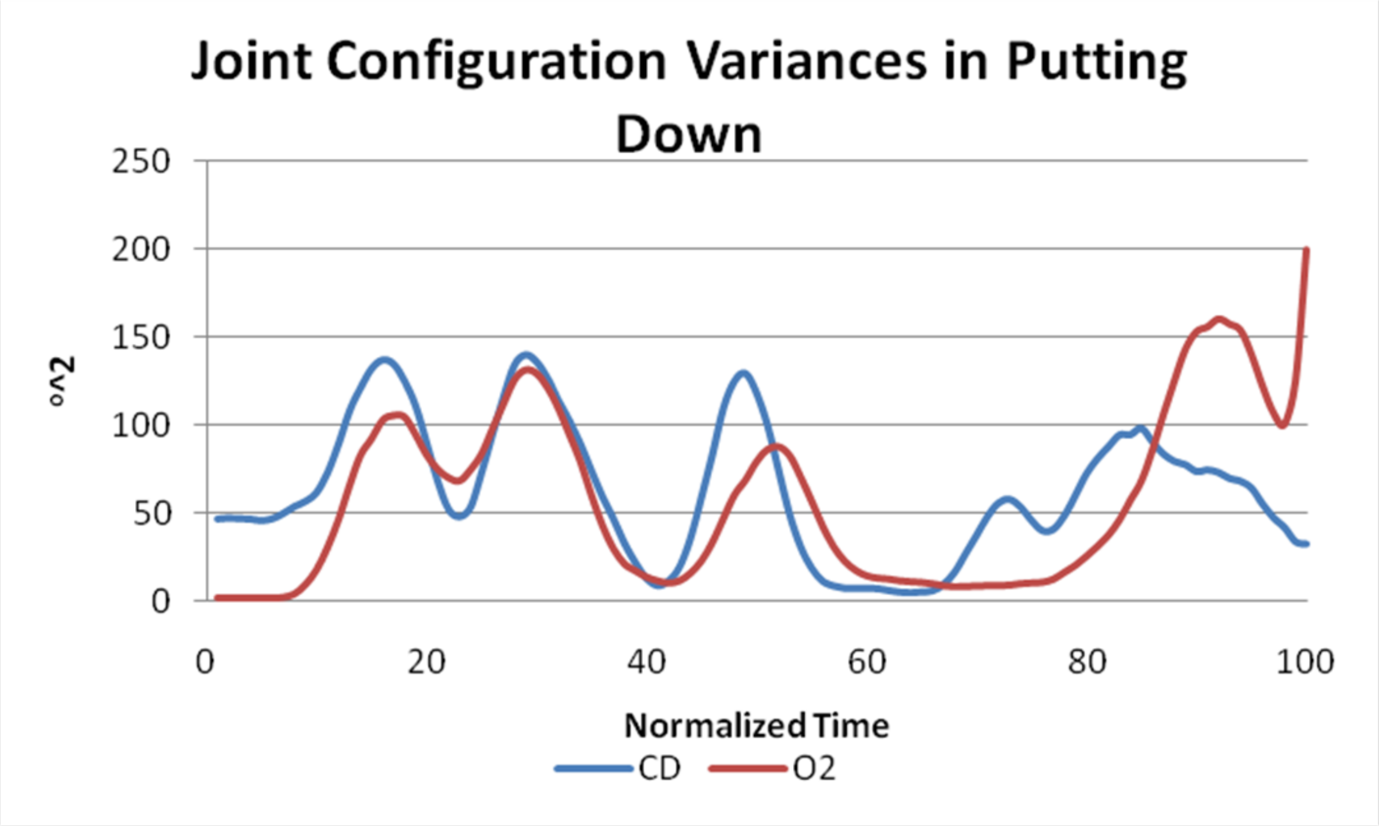
# Moving the upper limb vertically with or without a load (endpoint variances)



# Moving the upper limb vertically with or without a load (joint configuration variances)



# Moving the upper limb vertically with or without a load (joint configuration variances)



## Redundancy in the human musculoskeletal system

- Human movements are characterized by the production of desired motor output by redundant systems.

- **Redundancy** in this context means: that 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.

- **The issue is to discover rules used by the central nervous system (CNS) when it generates a unique solution for a problem that has a set of different available solutions**

# Redundant joint configurations

Joint space of an n-joint limb is the space of n-dimensional vectors with coordinates related to individual joint rotations.

e.g. the joint configuration of an n-joint system is

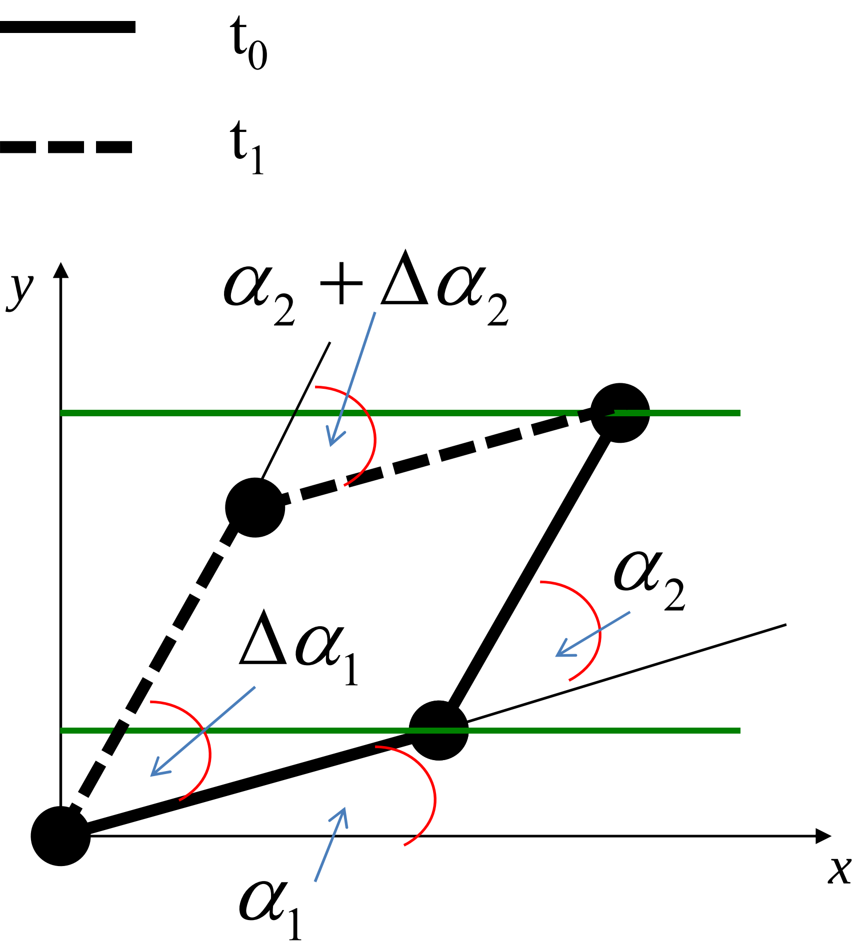
$$\boldsymbol{\alpha}(t) = (\alpha_1(t), \alpha_2(t), \ldots, \alpha_n(t)).$$

The relation between the change of position of the endpoint **Δp** of an n-joint limb and the change of joint configuration (Δ〈) is described locally by a mapping between the external workspace of the endpoint and the intrinsic joint-space of the limb:

$$\Delta \mathbf{p}(t) = \mathbf{J}^* \, \Delta\alpha(t)$$

where **J** is the Jacobian.

# Redundant joint configurations




It may occur that **Δα(t)** is not zero but the corresponding change of endpoint position **Δp** is zero.

This happens if **Δα(t)** belongs to the **Nullspace of the Jacobian** (Nul(J))

In this case the change in joint configuration doesn't cause change in endpoint position.

# Informal meaning of Jacobian

## - in kinematics and studies in joint synergies:

**A matrix of relations between changes in joint angles (in state space) and changes in a performance variable (in work space) to be controlled (e.g. endpoint position).**

## - in studies of muscle synergies: **A matrix of relations between small changes in muscle length and changes in joint angles.**

**The size of the Jacobian is determined by the dimension of the state space and the dimension of the workspace. For instance for planar movements of a 3-joint limb the Jacobian is a 2x3 matrix at any instant.**

# Manifolds

- Formally, every point of an *n*-dimensional manifold has a neighborhood homeomorph to the *n*-dimensional Eucledean space $\mathbb{R}^N$.
- Hence an *n*-dimensional manifold can be considered as a locally linear *n* dimensional space.
- E.g.: most human movements are the results of rotations around the joints. **As a consequence of such rotations the endpoint of a human limb moves on intersections of spheres or circles that are 3 and 2 dimensional manifolds respectively.**

# Moving the upper limb vertically with or without a load

If the Jacobian is known than $\mathbb{R}^N$ can be decomposed into the direct sum of to linear space: the Nulspace of J and the subspace orthogonal to the Nulspace:

$$\mathbb{R}^N = \mathrm{Nul(J)} \oplus \mathrm{Nul(J)}^{\perp}$$

The variance of angular configurations can also be decomposed into two compnents:

- Variance of joint configurations that lies within Nul(J) do not effect the position of the endpoint (**compensated variance**).

- Variance that lies in $Nul(J)^{\perp}$ do effect and change the position of the endpoint (this is called uncompensated variance).

$$Var_{total} = Var_{Comp} + Var_{Uncomp}$$

## Variances of limb movements – The good and the bad variance

- The principle of controlled and uncontrolled manifolds.
- **The structure of variance:** The **total variance** is decomposed to "**good**" variances and "**bad**" variances.

"**good**" variances are those variances of the limb movement that **do not effect the successful execution of the motor task (compensated variance).**

"**bad**" variances  are those variances that **do effect the success of the execution of the motor task (uncompensated variance).**

Detailed description about these principle is found in:  Domkin D, Laczko J, Djupsjöbacka M, Jaric S and Latash  ML (2005) : Joint angle variability in 3D bimanual pointing: uncontrolled manifold analysis.  Exp. Brain Research, V.163.

That component of the change of joint configurations ($\Delta\alpha$ ) which is parallel to the UCM is obtained by its projection onto Nul(J) and is denoted by $\Delta\alpha^{UCM}$.

If DV is the dimension of the task variable and DF is the number of independent joint angles, than the dimension of Nul(J) is m=DF-DV and the projection of $\Delta\alpha$ into the nullspace is:

$$\Delta\alpha^{UCM} = \sum_{i=1}^{m} \langle \Delta\alpha, ei \rangle * ei$$

Where $\mathbf{e1}, \mathbf{e_2}, \ldots, \mathbf{e_m}$ are independent vectors spanning Nul(J).
The component that is orthogonal to the null space is:

$$\Delta\alpha^{ORT} = \Delta\alpha - \Delta\alpha^{UCM}$$

# Structure of variance

$$V^{TOT} = \sum_{k=1}^{N} ((\Delta\alpha_k)^2 / (N * DF)$$

In order to investigate how changes in joint configuration **(Δα)** affects the endpoint position **(p)** , we partitioned the total joint variance ($V^{TOT}$) per degree of freedom into two components.

**1) uncompensated variance $V^{UN}$**, which affects the endpoint position and corresponds to the variance orthogonal to the uncontrolled manifold (UCM).

$$V^{UN} = \sum_{k=1}^{N} ((\Delta\alpha_k{}^{\mathbf{ORT}})^2 / (N * DV)$$

N is the number of repetitively executed movement trials

# Structure of variance

In order to investigate how changes in joint configuration (**Δα**) affects the endpoint position (**p**) , we partitioned the total joint variance per degree of freedom into two components.

**2) compensated variance $V^{COMP}$**, which do not affect the endpoint position and corresponds to the variance within the UCM manifold (subspace).

$$V^{COMP} = \sum_{k=1}^{N}((\Delta\alpha_k{}^{\mathbf{UCM}})^2 / \left(N*\left(DF-DV\right)\right)$$

N is the number of repetitively executed movement trials

**If the compensated variance is dominant in this partition then the task variable is well stabilized.**

**The neural command may limits the variability of the elemental variables in directions orthogonal to the UCM more than within it.**

The UCM approach has been successfully applied to studies of

- whole-body actions,
- multi-finger force production,
- multi-joint limb movements

It has also been used to discover and quantify atypical synergies in neurological patients, persons with Down syndrome and healthy elderly subjects

Detailed refernces in: Domkin D, Laczko J, Djupsjöbacka M, Jaric S and Latash ML (2005) : Joint angle variability in 3D bimanual pointing: uncontrolled manifold analysis. Exp. Brain Research, V.163.

# The main question – What is stabilized by the CNS?

- Endpoint position
- Muscle activity
- Joint rotation
- Distance from an external target
- Center of mass of the body or different segments
- Number of degree of freedoms applied
- Distance between different parts of the body
- Execution time
- Accuracy
- Execution speed
- Direction of muscle force
- Magnitude of muscle force

# The main question – What is stabilized by the CNS?

- **Because of the redundancy problem** (the human skeletal system has more muscles than needed to solve a given motor task with the required degrees of freedom (DoF))
  - **It would be necessary to reveal how the central nervous system (CNS) makes its choices in selecting the appropriate solution of a motor task**, which has infinite number of solutions.
  - This is the so called **muscle synergy** problem
  - Synergy: working together - Well coordinated sequences of control signals to several muscles participating in a motor task.

- **Bernstein (the pioneer of the muscle synergy problem)** stated that the CNS „have” many **pre-defined sets of muscle synergy strategies** to be able to handle the redundant DoF through
  - Solving optimalization criterias:

    minimizing energy, jerk, or movement time
  - Central representation of future movements (stored movement patterns)
  - Adding constraints
  - Dealing with external perturbance to maintain an equilibrium

## The main question – What is stabilized by the CNS?

- **Just after Bernstein** reported the muscle synergy theory an another suggestion of CNS DoF handling was revealed:
  - **The CNS uses all the DoF's  but it organizes them into flexible task related variables**
- **This suggestion** gave the mathematical basis of a computational method called **uncontrolled manifold hypothesis (UCM)**
- **The UCM analysis assumes:** „the controller acts in the state space of independent variables and creates in that space a sub-space (a UCM) corresponding to a value of **an important performance variable that needs to be stabilized**. "Then, the controller limits the variability of the elemental variables in directions orthogonal to the UCM more than within the UCM." [Domkin et al. 2004]

# Summary

- **The main and the most important question of motor control after Bernstein is:**

  1. **What is controlled by the central nervous system (CNS)?**
  2. **How motor control is done by the CNS?**
- **The main issue is to find a solution to synergy and redundancy problem is the UCM(uncontrolled manifold) analysis and the investigation of the structure of the variance**
  - **Therefore: variances of different limb movements (upper and lower limb) of the endpoint and joint configuration were computed.**
- **Investigated movements: (comparison of PD and stroke patients with healthy subjects; holding analysis of healthy subjects)**

# Suggested literature


- Domkin D, Laczko J, Djupsjöbacka M, Jaric S and Latash ML (2005) Joint angle variability in 3D bimanual pointing: uncontrolled manifold analysis. Exp. Brain Research, V.163.

- Bernstein NA (1967) The co-ordination and regulation of movements. Pergamon, Oxford

- Gelfand IM, Tsetlin ML (1966) On mathematical modeling of the mechanisms of the central nervous system. In: Gelfand IM, Gurfinkel VS, Fomin SV, Tsetlin ML (eds) Models of the structural-functional organization of certain biological systems. Nauka, Moscow, pp 9–26 (in Russian; translation in 1971 edn, MIT Press, Cambridge, MA)

- Domkin D, Laczko J, Jaric S., Hakan J., Latash ML, (2002), Structure of joint variability in bimanual pointing tasks, Exp. Brain Research 143,11-23

# Suggested literature


- Scholz JP, Schoner G (1999) The uncontrolled manifold concept: identifying control variables for a functional task. Exp Brain Res 126:289–306
- Scholz JP, Schoner G, Latash ML (2000) Identifying the control structure of multijoint coordination during pistol shooting. Exp Brain Res 135:382–404
- Latash ML (1996) How does our brain make its choices? In: Latash ML, Turvey MT (eds) Dexterity and its development. Erlbaum, Mahwah, NJ, pp 277–304
- Latash ML, Scholz JF, Danion F, Schoner G (2001) Structure of motor variability in marginally redundant multifinger force production tasks. ExpBrainRes 141:153–165
- http://www.bsu.edu/web/jkshim/mc/ucm.htm