MODELING AND EXPERIMENTAL INVESTIGATIONS OF HUMAN UPPER LIMB

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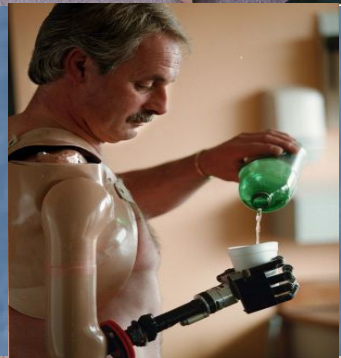
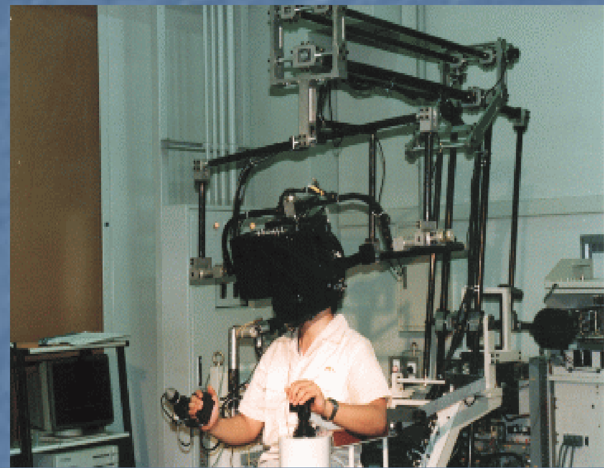
For designing and developing technical devices (orthesis, prosthesis, rehabilitation robots, teleoperators etc.) for human upper limb its biomechanics has to be well known

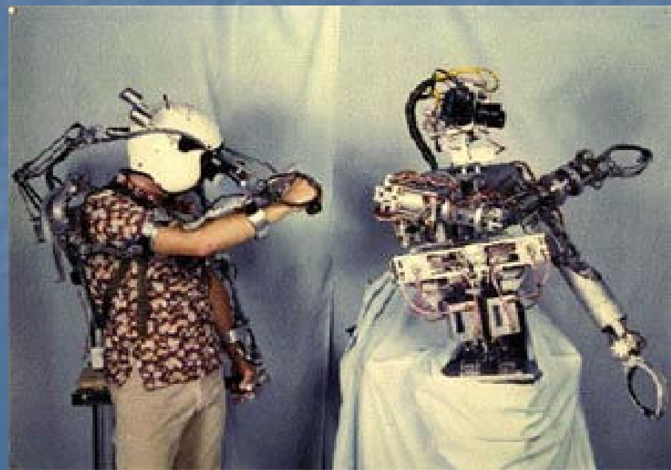
TEHNICAL DEVICES

Antropomorphic robots



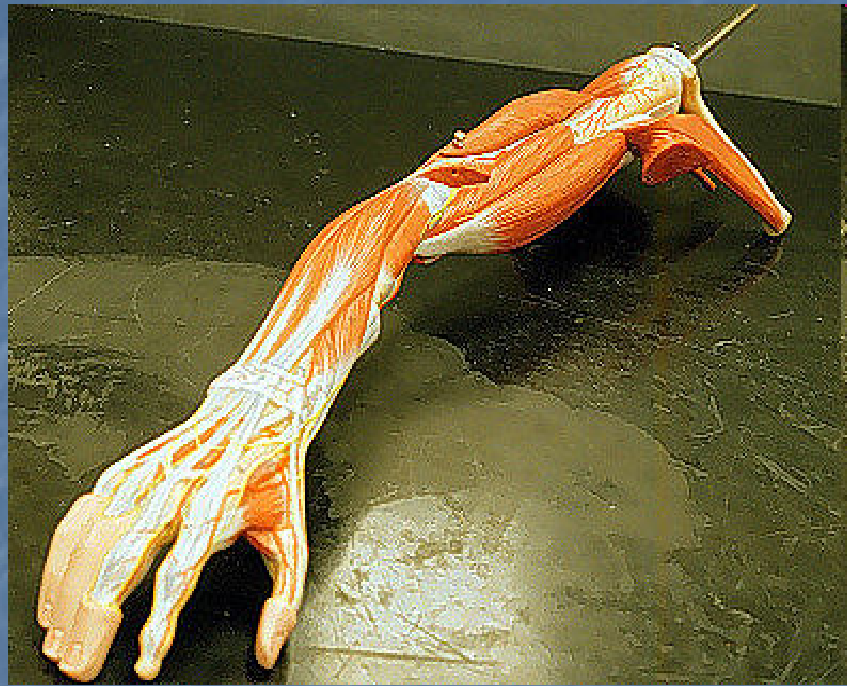
Prosthetic devices

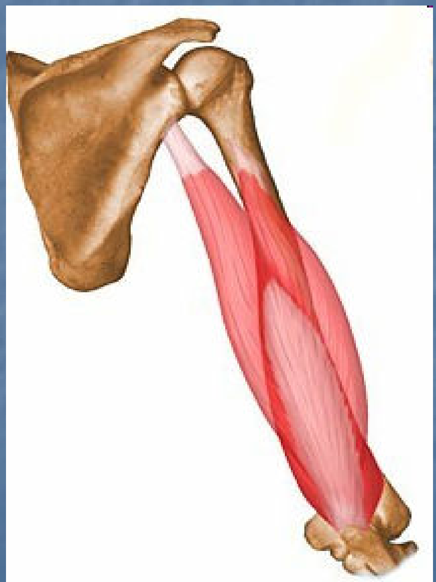


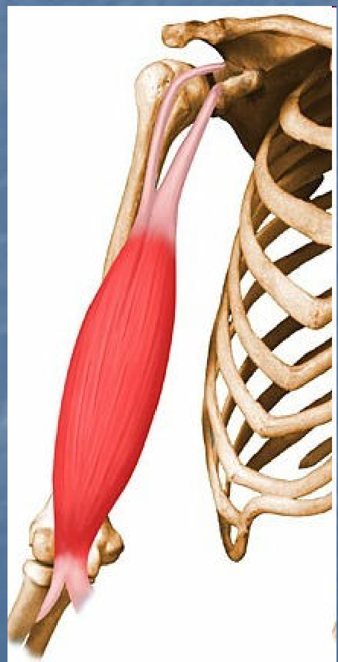


Teleoperators

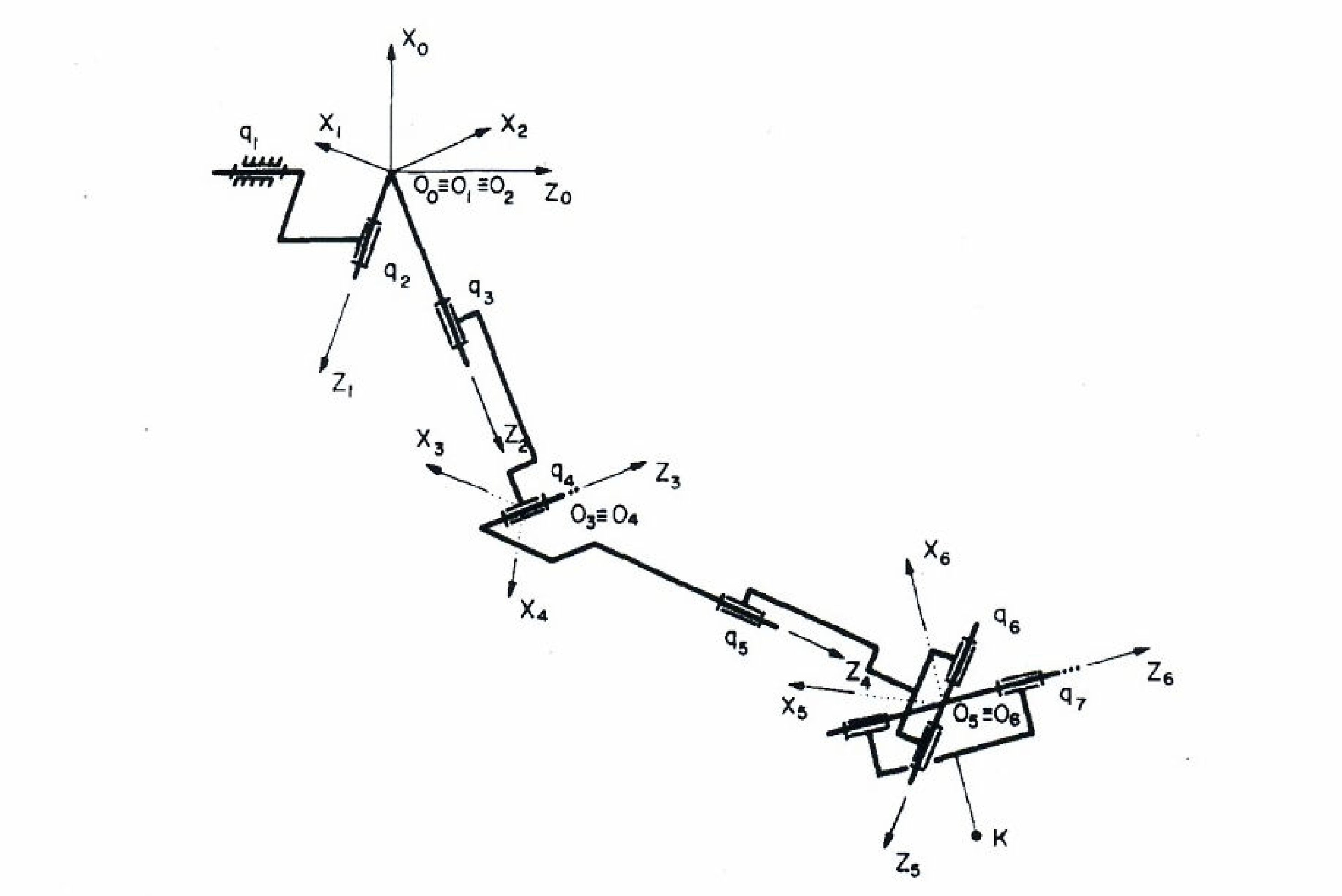
ANATOMICAL OBJECT







7 DOF - shoulder joint (3 – flexion/extension, abduction/adduction, external-internal rotation), elbow joint (2 – flexion/extension, pronation/supination) and wrist joint (2- flexion/extension, abduction/adduction); many muscles including multiarticular ones



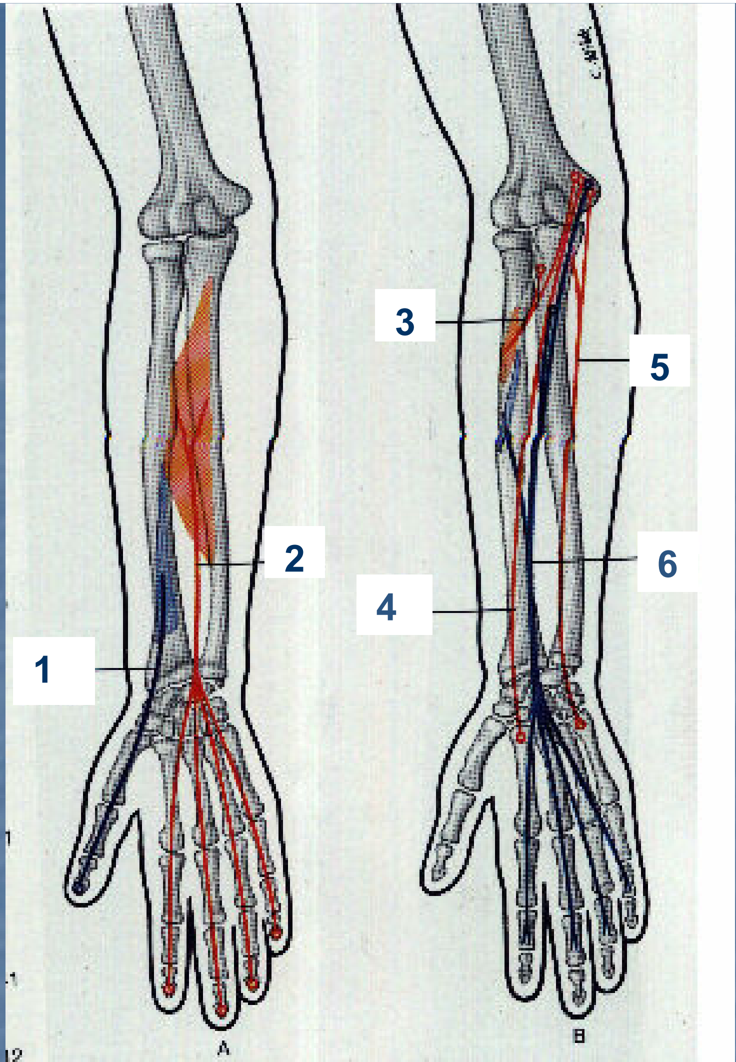
Kinematic scheme of the upper human limb:general coordinates

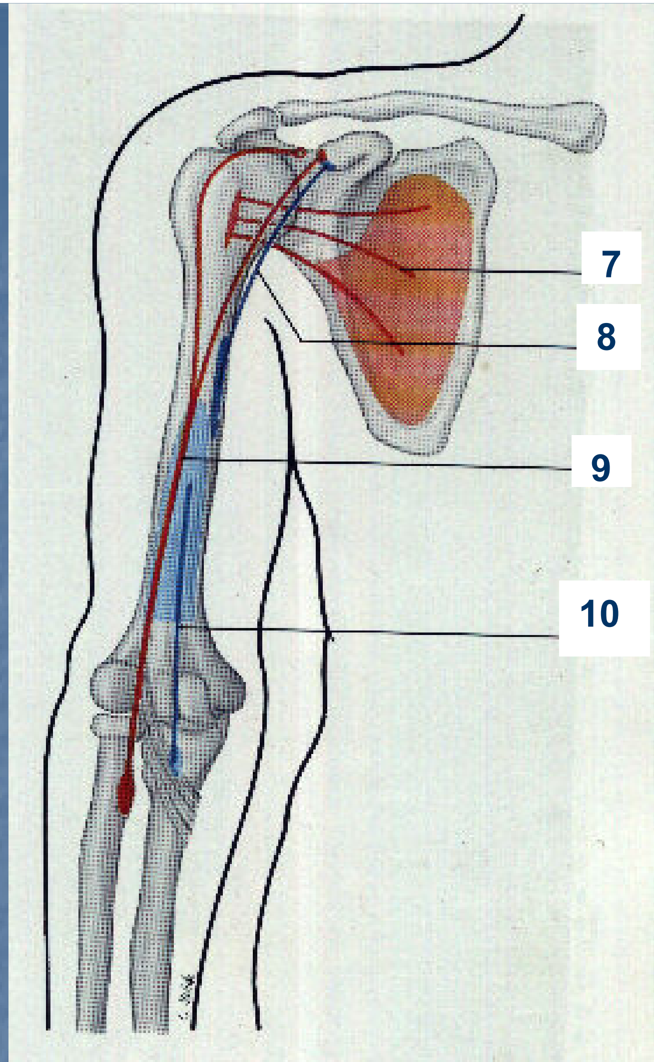
q_1- abduction/adduction in shoulder; q_2 – flexion/extension in shoulder;

q_3 – internal/external rotation in shoulder; q_4 - flexion/extension in elbow ;

q_5 - pronation/supination in elbow; q_6 – flexion/extension in wrist;

q_7 – abduction/adduction in wrist

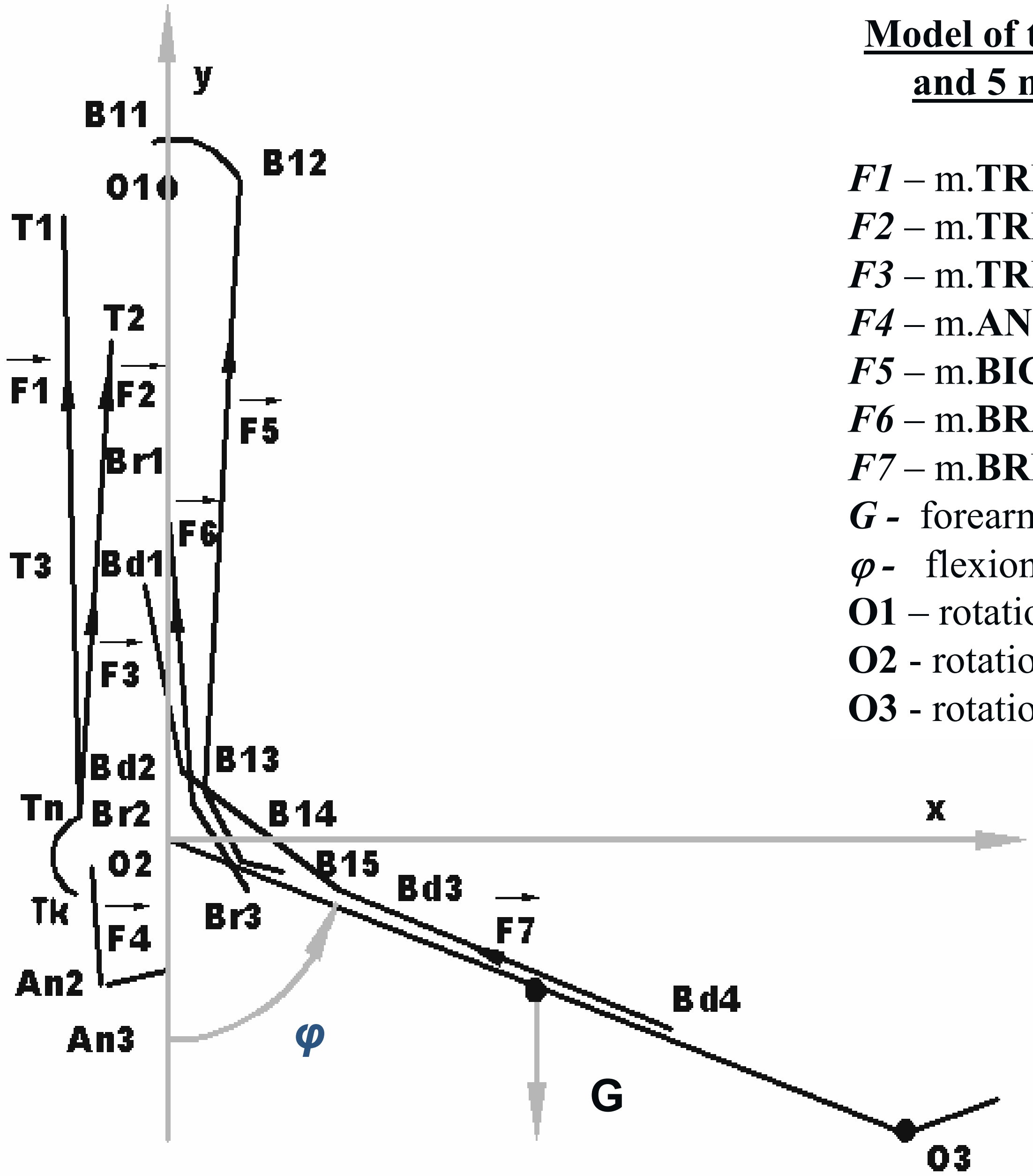




MUSCLE FORCES MODELING (by stright lines or by centroides)

1- m.flexor polisis longus; 2 – m.flexor digitorum profundus; 3 – m.pronator teres;
4 - m.flexor carpi radialis; 5 – m.flexor carpi ulnaris; 6 – m.flexor digitorum superficialis;
7 – m.subscapularis; 8 – m.coracobrachialis; 9 – m.biceps brachii; 10 – m.brachialis.

Model of the elbow joint with one DOF and 5 muscles in the sagital plane



F1 – m.**TRI** (c.longum)
F2 – m.**TRI** (c.laterale)
F3 – m.**TRI** (c.mediale)
F4 – m.**ANC**
F5 – m.**BIC**
F6 – m.**BRA**
F7 – m.**BRD**
***G* -** forearm and hand weight
***φ* -** flexion angle
O1 – rotation centre in shoulder joint
O2 - rotation centre in elbow joint
O3 - rotation centre in wrist joint

One moment equation with 7 unknown muscle forces

So, we have indeterminate problem

(1) $\sum a_{1i} x_i^2 = A_1 \qquad \Rightarrow A_1 = -d_G |G| + I_{zz} \quad - |M_o(F_{ext})|$

$$x_i^2 = F_i \quad i=1,2,\dots 7$$

Optimization task

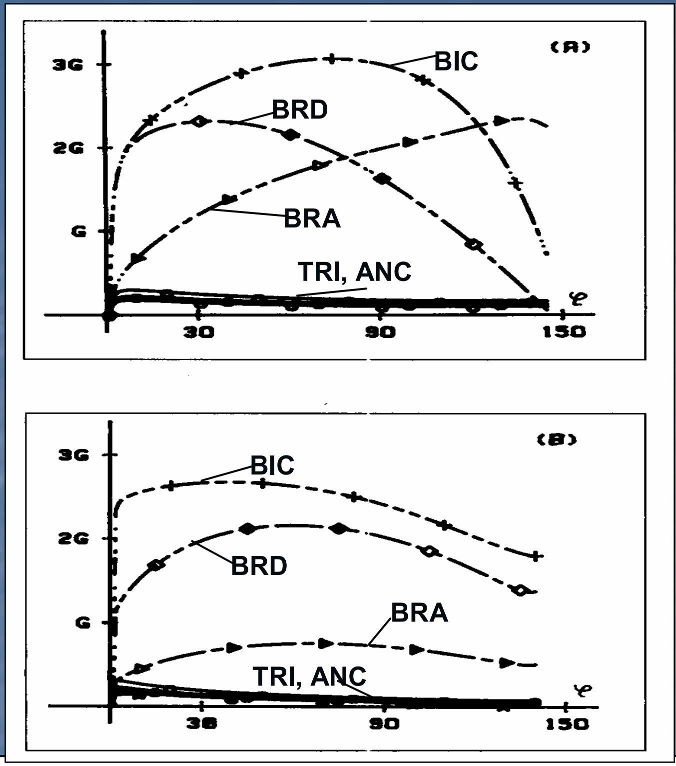
To determine the extremum of a function $Z=\sum c_i |F_i|^n$ (n>1)

at the constraints (1) and inequality constraints $F_i > 0$

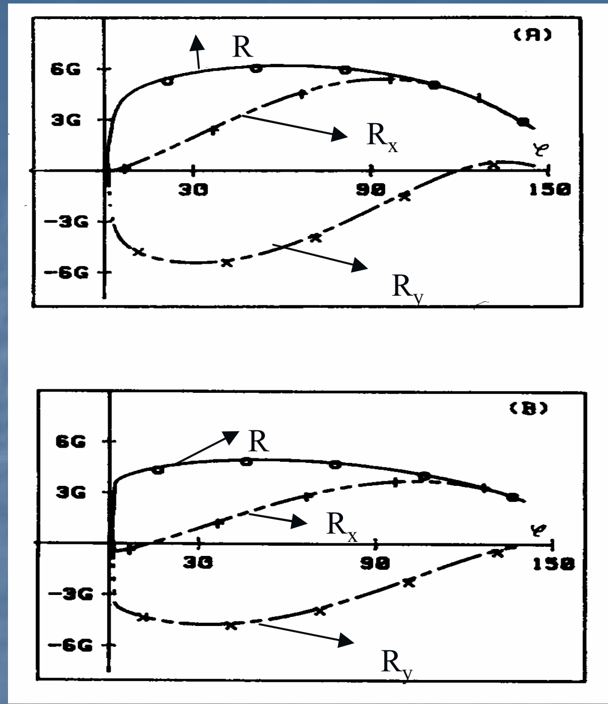
Analitical solution

(Lagrange multipliers method) →

$$|F_i| = x_i^2 = \frac{A_1 (a_{1i}/c_i)^{1/(n-1)}}{\sum_{j=1}^{7} a_{1j} (a_{1j}/c_j)^{1/(n-1)}}$$



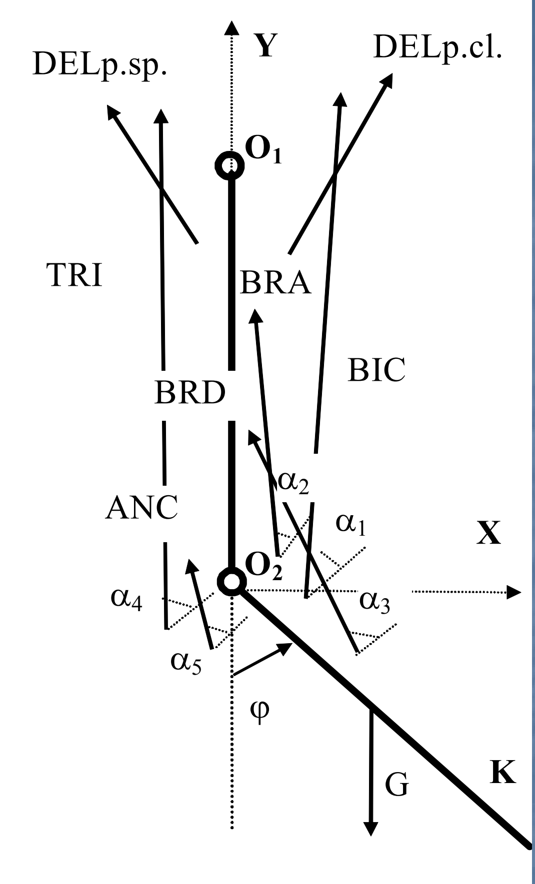
Calculated muscle forces with one and the same objective function but with different muscle force arms. Parameters of the objective function are: n=2,
c_1=-10, c_2=-8, c_3=-6, c_4= -4, c_5=0.2, c_6=0.3, c_7=0.5



Calculated joint reactions for the two cases

Proposed analytical form of the weight coefficients in the objective function $\sum c_i F_i^n$

$$c_i = \left| M_{ext} \right| \frac{d_{ext}}{d_i} (PCSA_i)^{n_1} (F_{imax})^{n_2} e^{(\Delta l_i - \alpha_i)}$$



Two DOF model in the sagital plane

7 unknown muscle forces

$$(1)\quad \sum_{i=1}^{5} d^{(e)}{}_i F_i = I_{zz}\ddot{\varphi} + G l_1 sin(\varphi) = M_{ext}$$

$$R_x = m l_1 (\ddot{\varphi}\cos\varphi - \dot{\varphi}^2 \sin\varphi) - \sum_{i=1}^{5} F_i cos(\alpha_i + \varphi)$$

$$R_y = m l_1 (\ddot{\varphi} sin\,\varphi + \dot{\varphi}^2 cos\,\varphi) + G - \sum_{i=1}^{5} F_i sin(\alpha_i + \varphi)$$

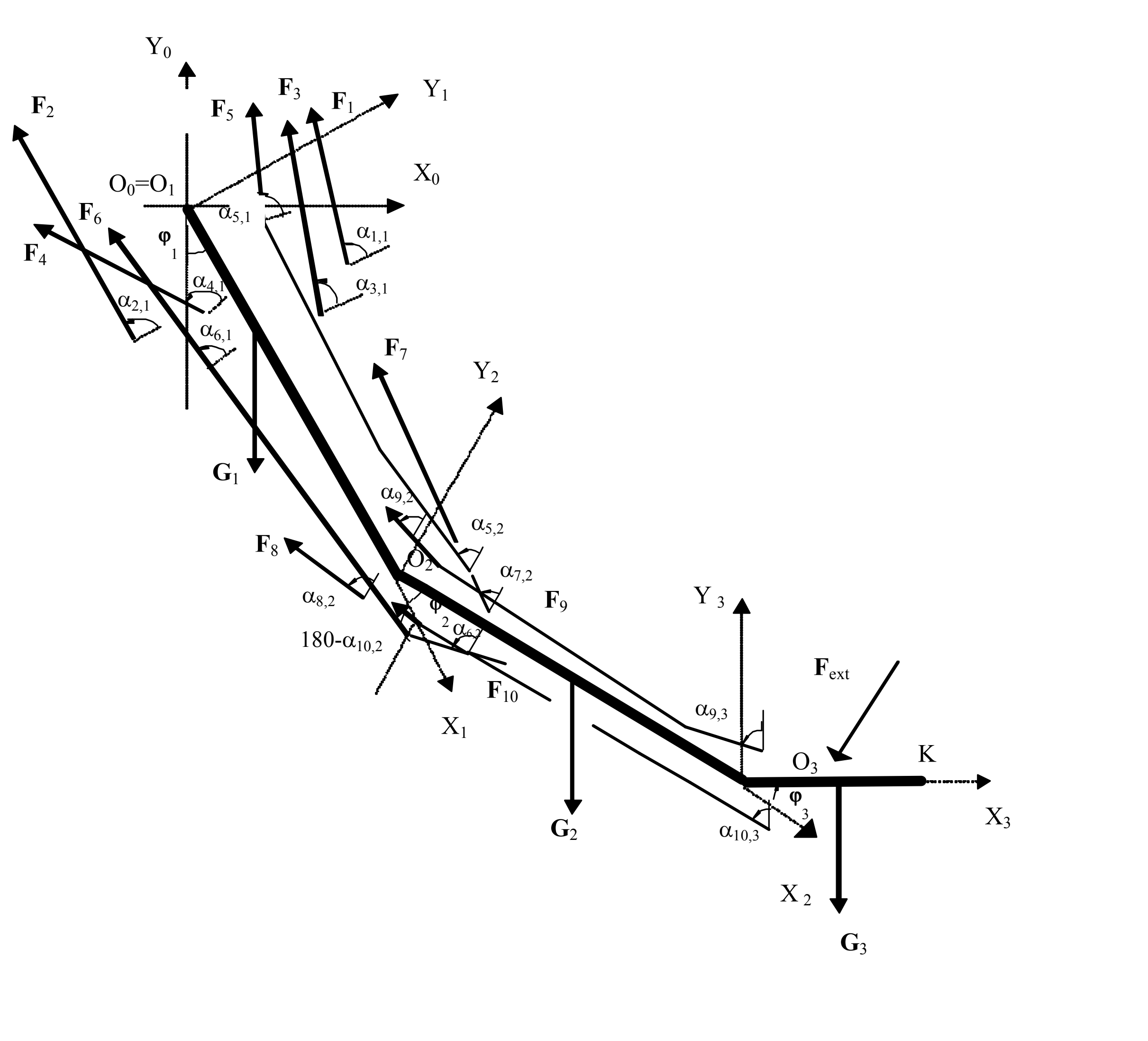
$$(2)\; d^{(s)}{}_1 F_1 - d^{(s)}{}_4 F_4 + d^{(s)}{}_6 F_6 - d^{(s)}{}_7 F_7 + l_2 (m l_1 (\ddot{\varphi}\cos\varphi + \dot{\varphi}^2 \sin\varphi) - \sum_{i=1}^{5} F_i cos(\alpha_i + \varphi)) = 0$$

Optimization task

min Z at the constraints (1) and (2) and $F_i > 0$

$$Z = k_1 R^{n1} + k_2 \Sigma (F_i / PCSA_i)^{n2}$$

MODEL WITH 3 DOF IN THE SAGITTAL PLANE



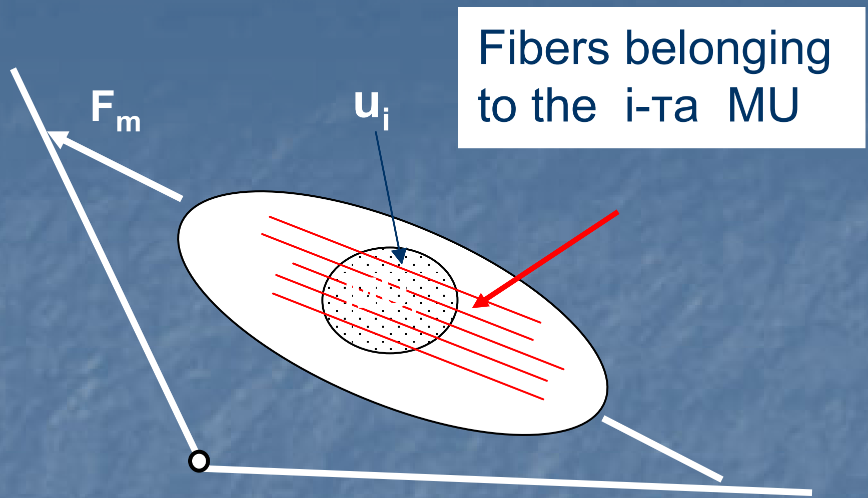
10 muscles : **DELp.cl., DELp.sp., COR, TMJ, BIC, TRI, BRA, ANC, FCR, EDI**, four of them biarticular

10 unknown muscle forces, three moment equations

What is inside the muscle?

What the human brain controls?

→ **MOTOR UNITS**



MU – the smallest functional part of the muscle which can be controlled individually

F_m – force of the whole muscle

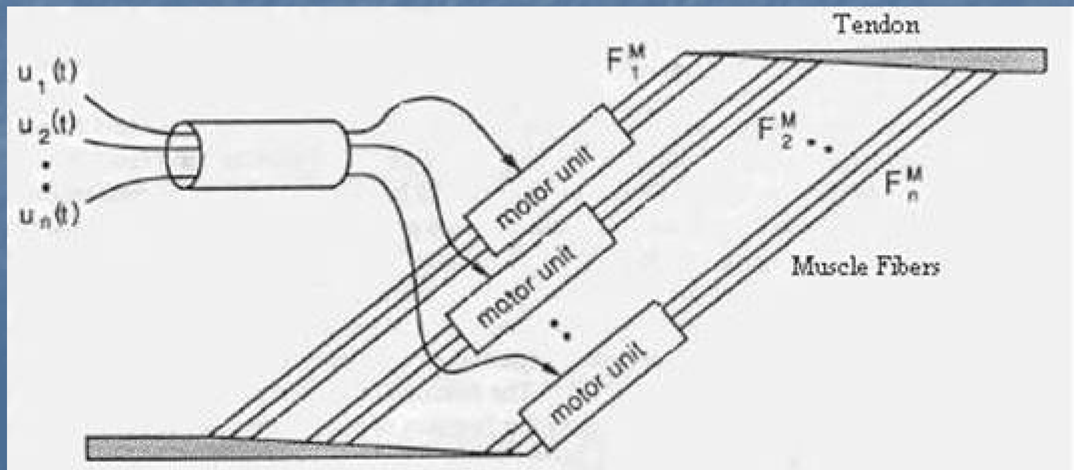
u_i – control signal for the i-th MU

According to ***Liddell and Sheruington (1925)****, a MU is its* α motoneuron, its axon and the group of muscle fibers controled by this neuron

Different motor units (MUs)
– slow

- fast resistant to fatique

- fast fatigable



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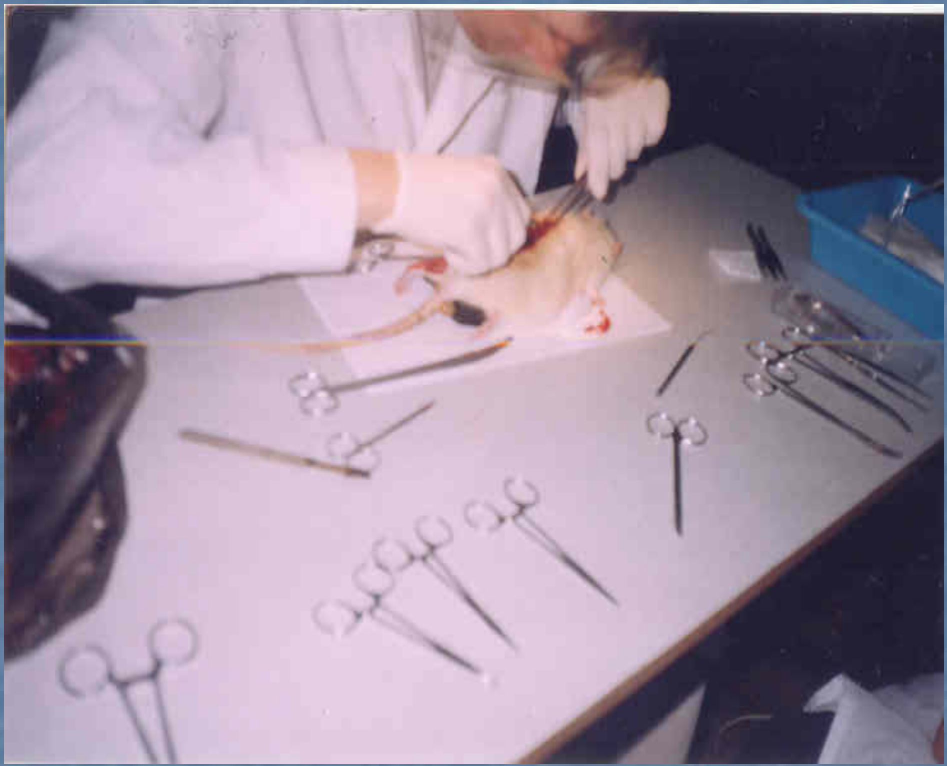
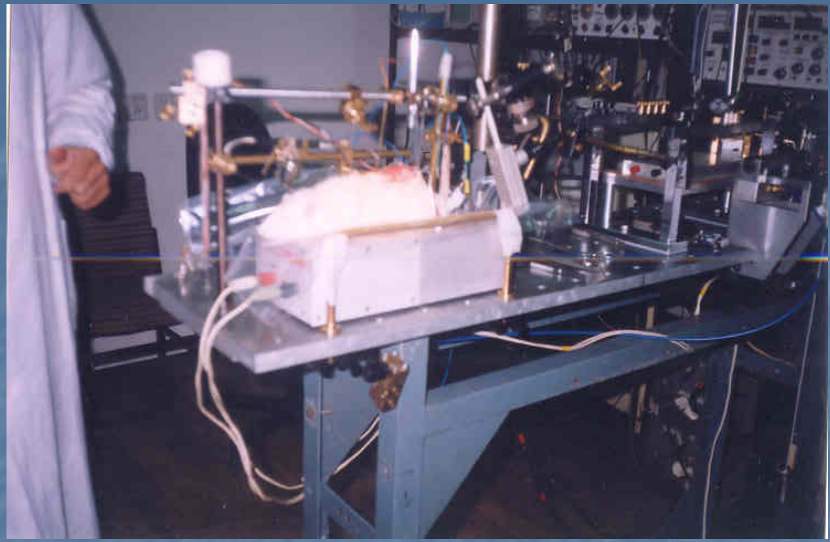
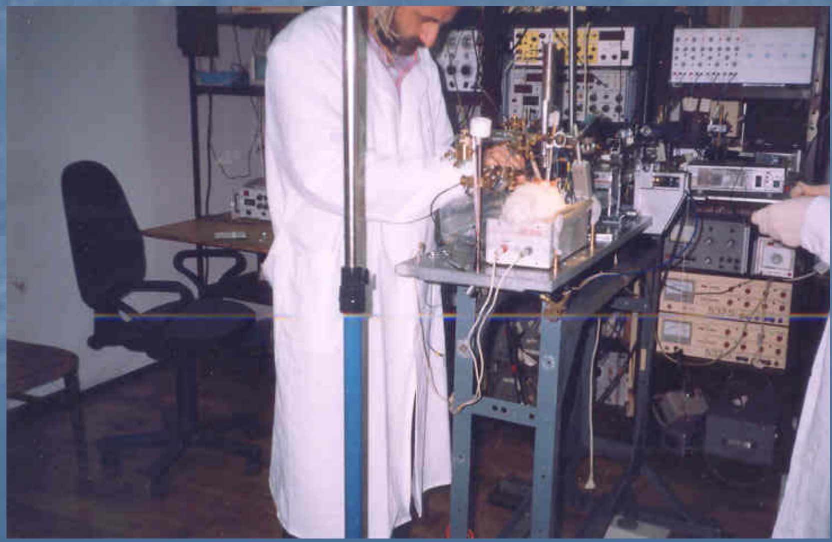




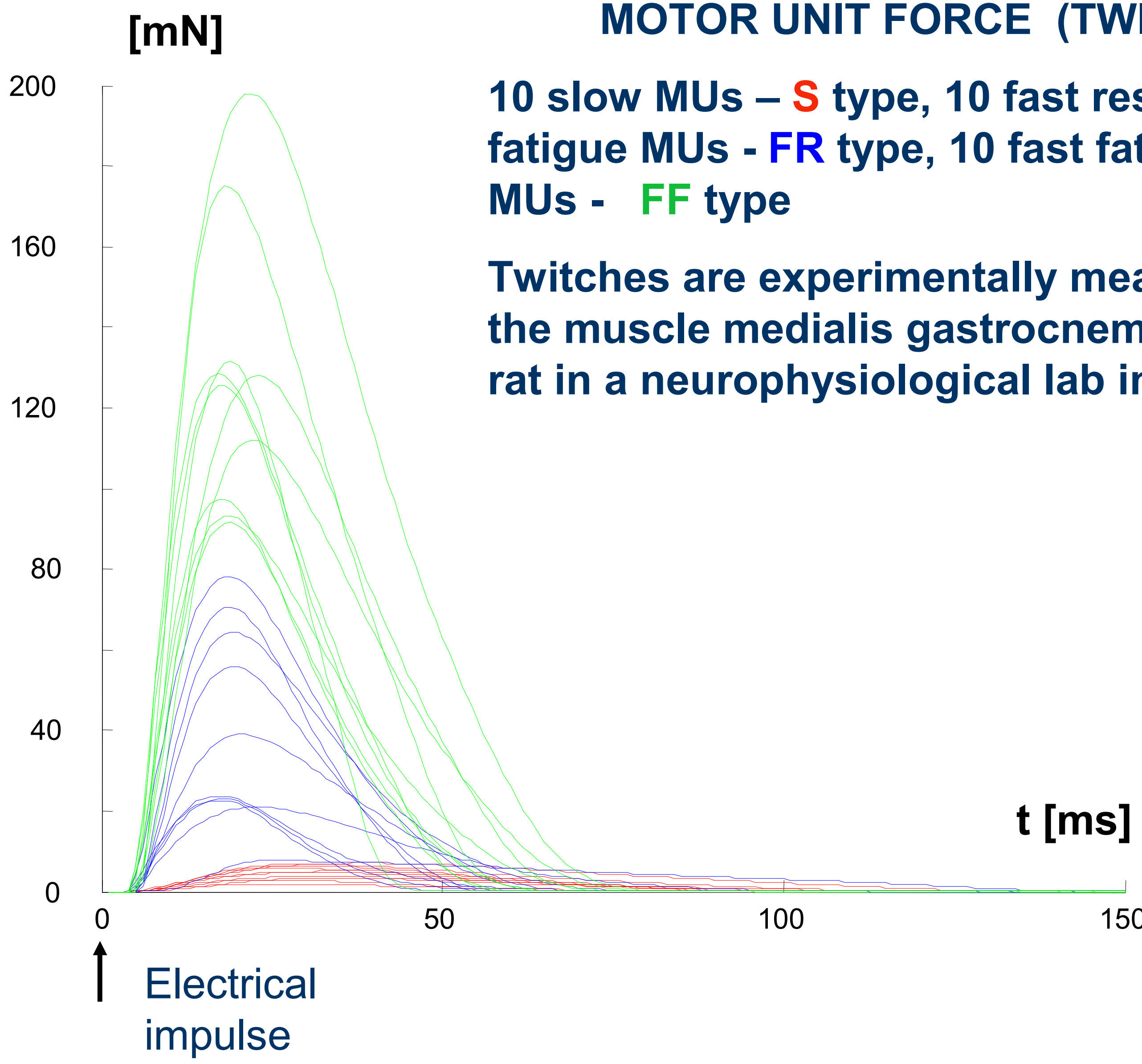
Experiments for recording force of
one MU of rat muscles

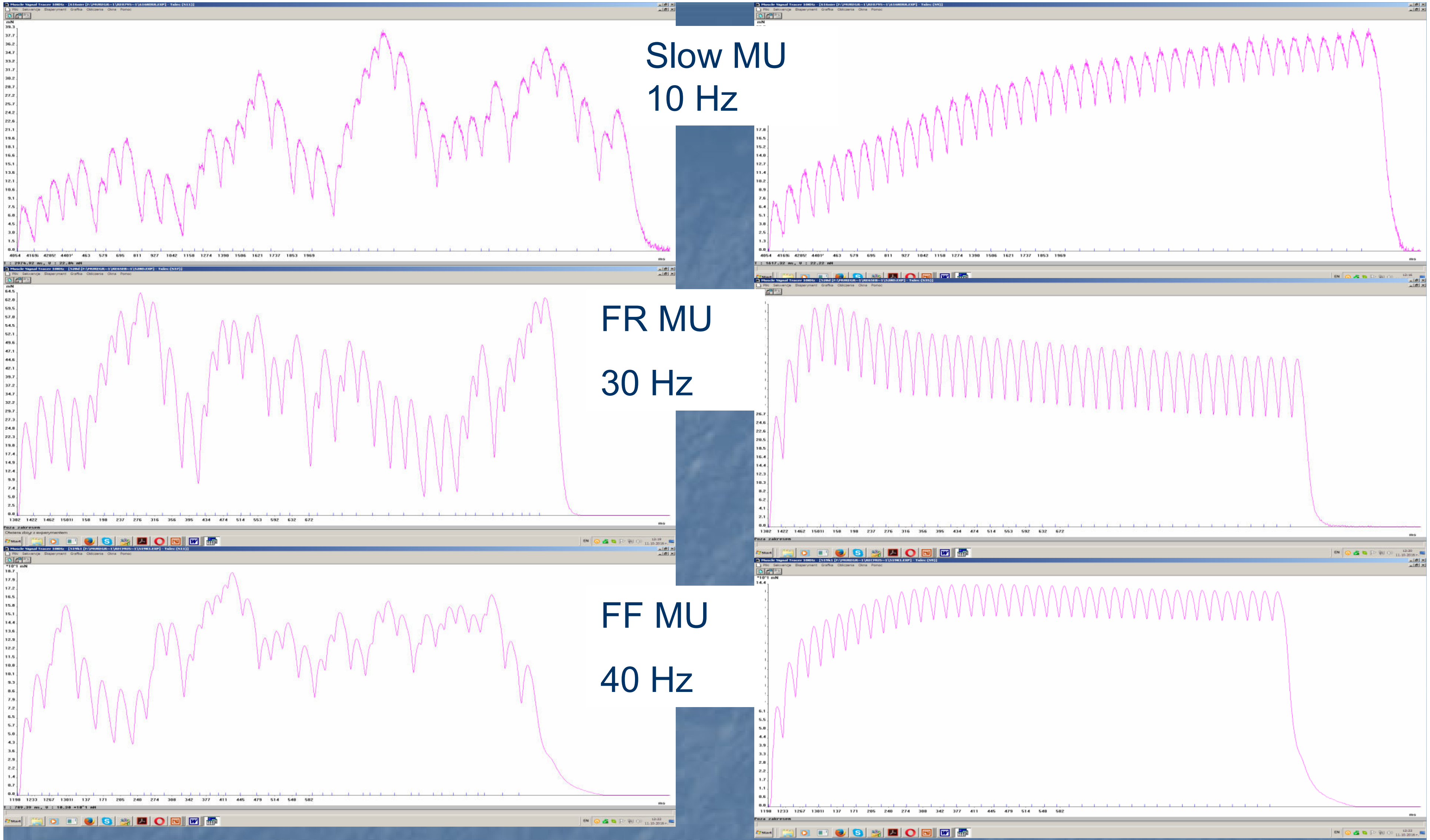


MOTOR UNIT FORCE (TWITCH)

10 slow MUs – S type, 10 fast resistant to fatigue MUs - FR type, 10 fast fatigable MUs - FF type

Twitches are experimentally measured on the muscle medialis gastrocnemius of a rat in a neurophysiological lab in Poznan





Experimental tetanic forces evoked by irregular and regular stimulation

(41 in number stimuli)

ELECTROMYOGRAPHIC SYGNALS (EMGs)

FROM A SURFACE MUSLE IS AN EVIDENCE

FOR ACTIVITY OF THE MOTOR UNITS

Electromyographic signals – registering and processing

Telemyo 2400

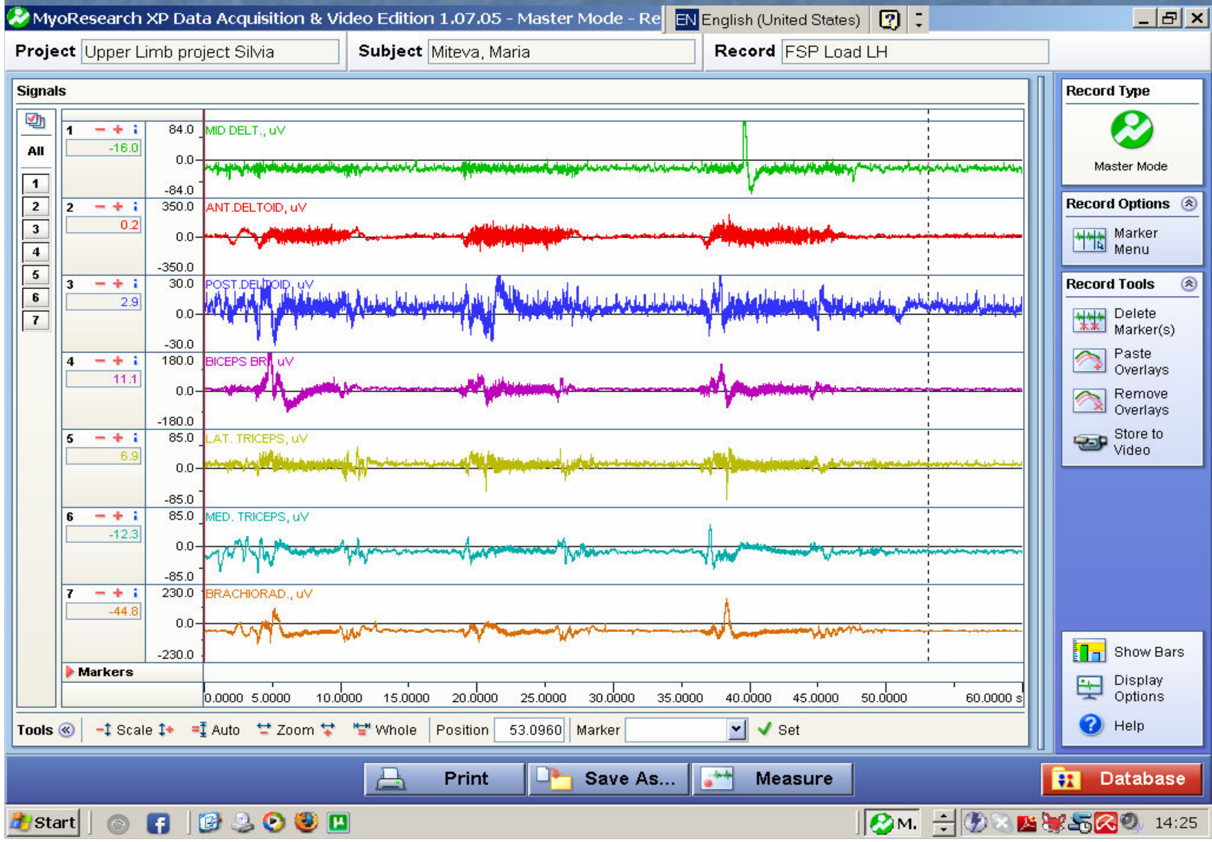
Surface sensors
Skintact-premier F-301

8 channels electromyographic system Telemyo 2400 G2 of Noraxon USA, Inc., 9 mm circle electrodes – “Skintact-premier” F-301, the signals are transferred to a laptop telemetrically and are saved on the hard disk. The skin surface is cleaned by alcohol and conductive gel is pasted.

EMG signals are registered from the following 6 surface muscles - m. deltoideus pars clavicularis (DELcla), pars acromialis (DELacr) and pars spinata (DELspi), m.biceps brachii (BIC), m.triceps brachii caput longum (TRI) and m.brachioradialis (BRD). Different motor tasks (static and dynamic) are performed with the right and the left upper limb.

Investigated patient – post-stroke survivor, left injured limb

Movement – maximal elbow flexion in the sagital plane with weight in hand from 0.5 kg

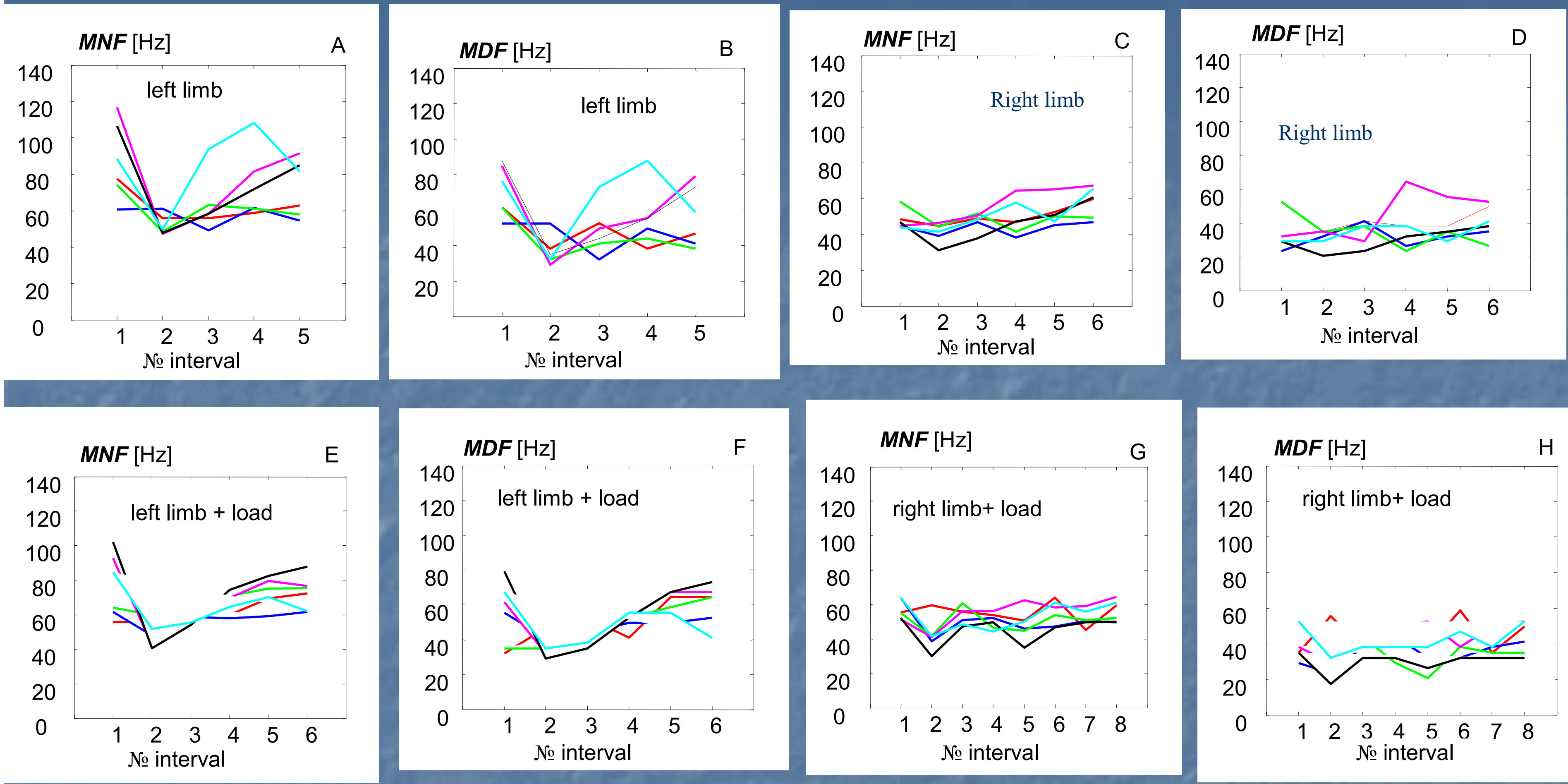


Non-procesed EMG signals

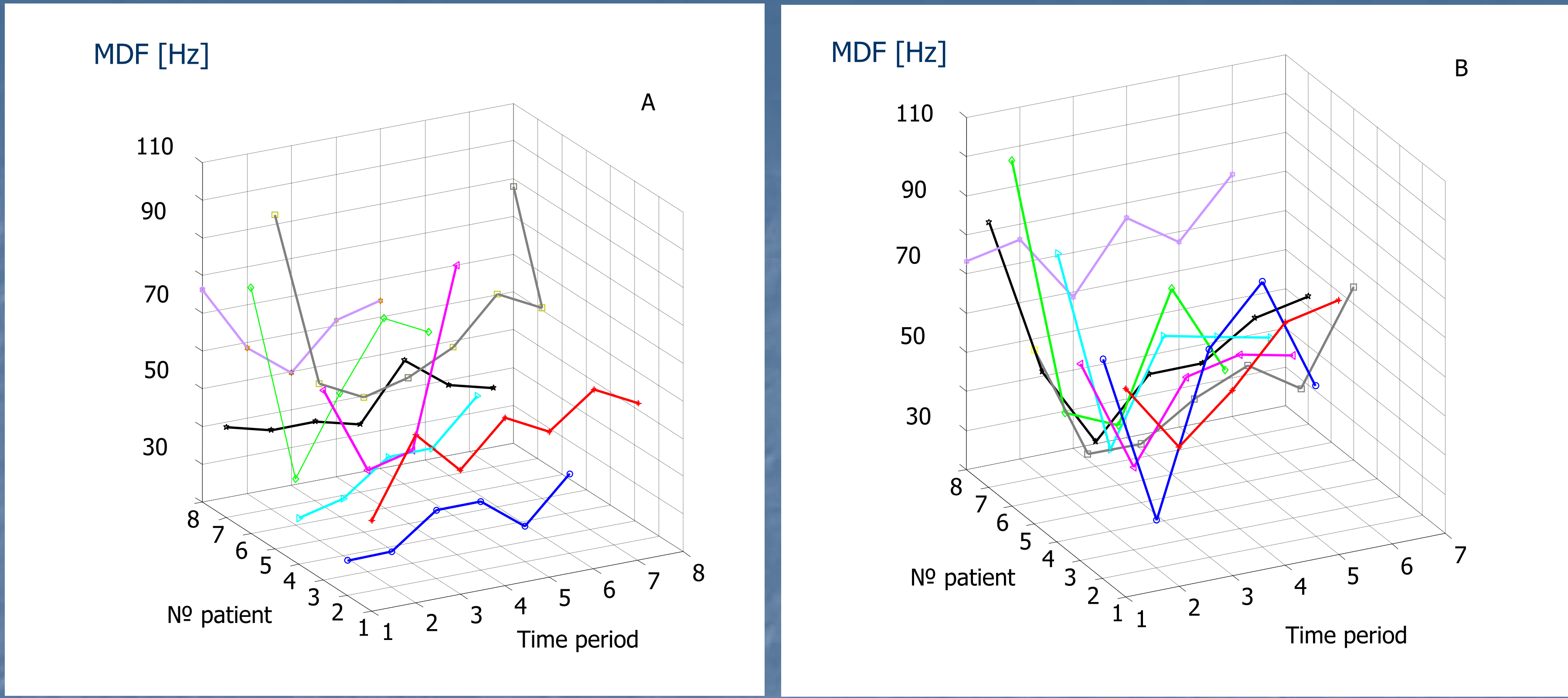
Motion – elbow flexion in the sagital plane with weight

Left injured limb

- Investigated volunteers – 10 post-stroke patients and 15 healthy subjects
- EMG signal processing: filtering, normalization, averaging, smoothing, Fast-Furie analysis, power/frequency analysis
- The aim is to compare healty limb with injured limb, respective left with right limb and to find parameters which are influenced by the stroke; to discover whether the muscles of the affected limb produce enough distinguished EMG signal to be used as control signal for an ortotic device



Mean (MNF) and median (MDF) frequencies for a patient during elbow flexion of the left and the right upper limbs without and with a load of 0.5 kg placed on the wrist (+load). The following colours are used for the 6 muscles: red – DELacr, blue – DELcla, green – DELspi, magenta – BIC, black – TRI, and cyan – BRD. The affected limb for this patient is the right one.



Calculated values of median frequency (MDF) of the muscle biceps for 8 patients with right ingured hand – movement elbow flexion in the sagital plane; equal time interval are considered from 0.3407 s.

A. Right limb B. Left limb. For different patients different colors are used.

The main conclusion is that there is no such calculated parameter which can distinguish statistically the muscles of the affected from the unaffected limb. Each subject has its own individual movement strategy. The more so, the calculated parameters are different for the dominant and non-dominant limb for healthy people. Some conclusions can be made however:

- **working frequency of more of the affected by stroke muscles decreases, hence more slow motor units are presented and working;**

- **the muscle coordination of the affected limb is disturbed, elbow flexion is performed with compensation movements in the shoulder;**

- **during motions the synergistic muscles of the affected limb use much more power than of the non-affected limb but an increase of the antagonistic co-activation is not observed;**

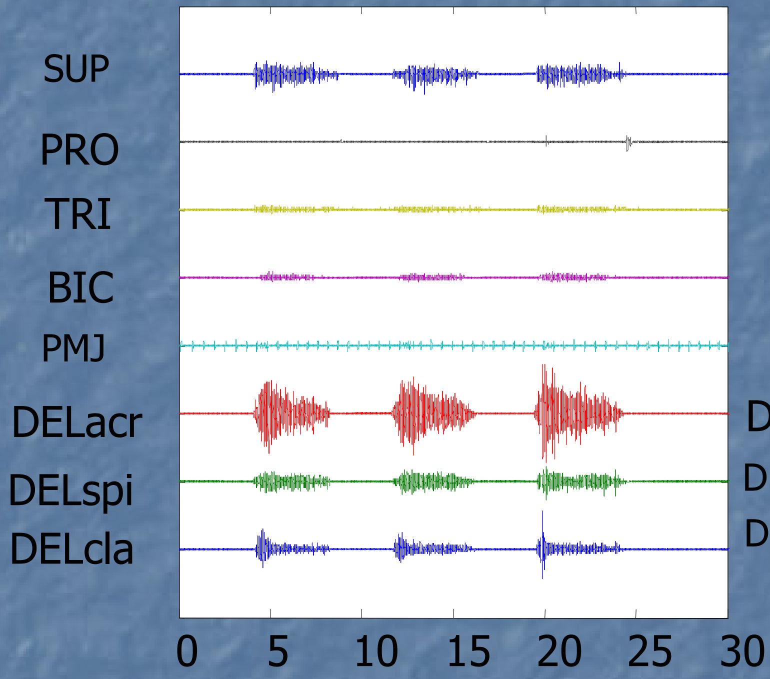
- **for elbow flexion motion in the sagittal plane using power/frequency analysis and calculating for equal time intervals median and mean frequencies and maximal power it was found that: the mean frequency is higher that the median both for patients and for healthy subjects; considerably decrease of these frequencies was found for three post stroke patients; calculated frequencies for the first (preparatory) time interval were nearly always higher in comparison with the other intervals; the maximal power is nearly zero during the first time interval and after that increases; the most power was calculated in flexor muscles; these powers were considerable bigger for the muscles of the injured limb; hence this parameter can be used for estimation of the muscle damage**

Can EMGs be used as control parameters

for different technical devices?

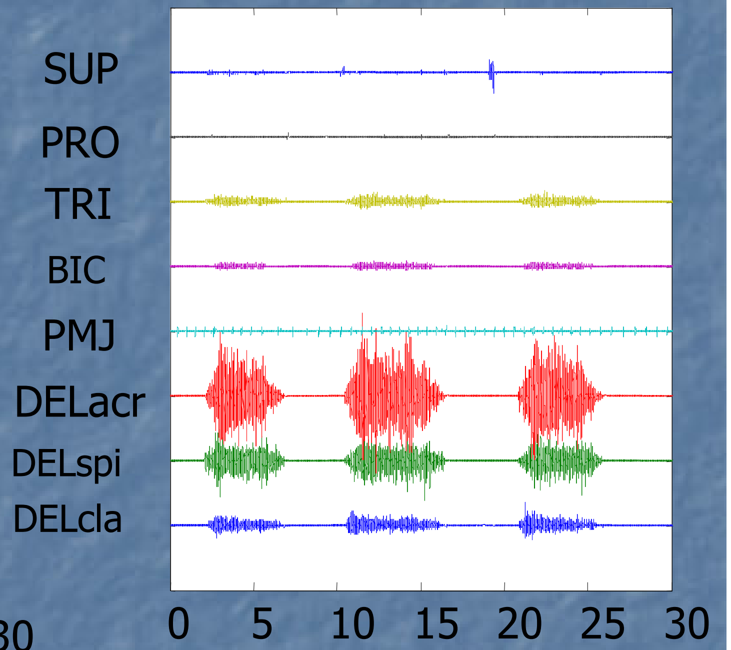
Registering and procesing EMG signals with aim to use them as control parameters for an orthoses of the upper limb. Two types of control – proportional and "on-off"

normalized EMGs



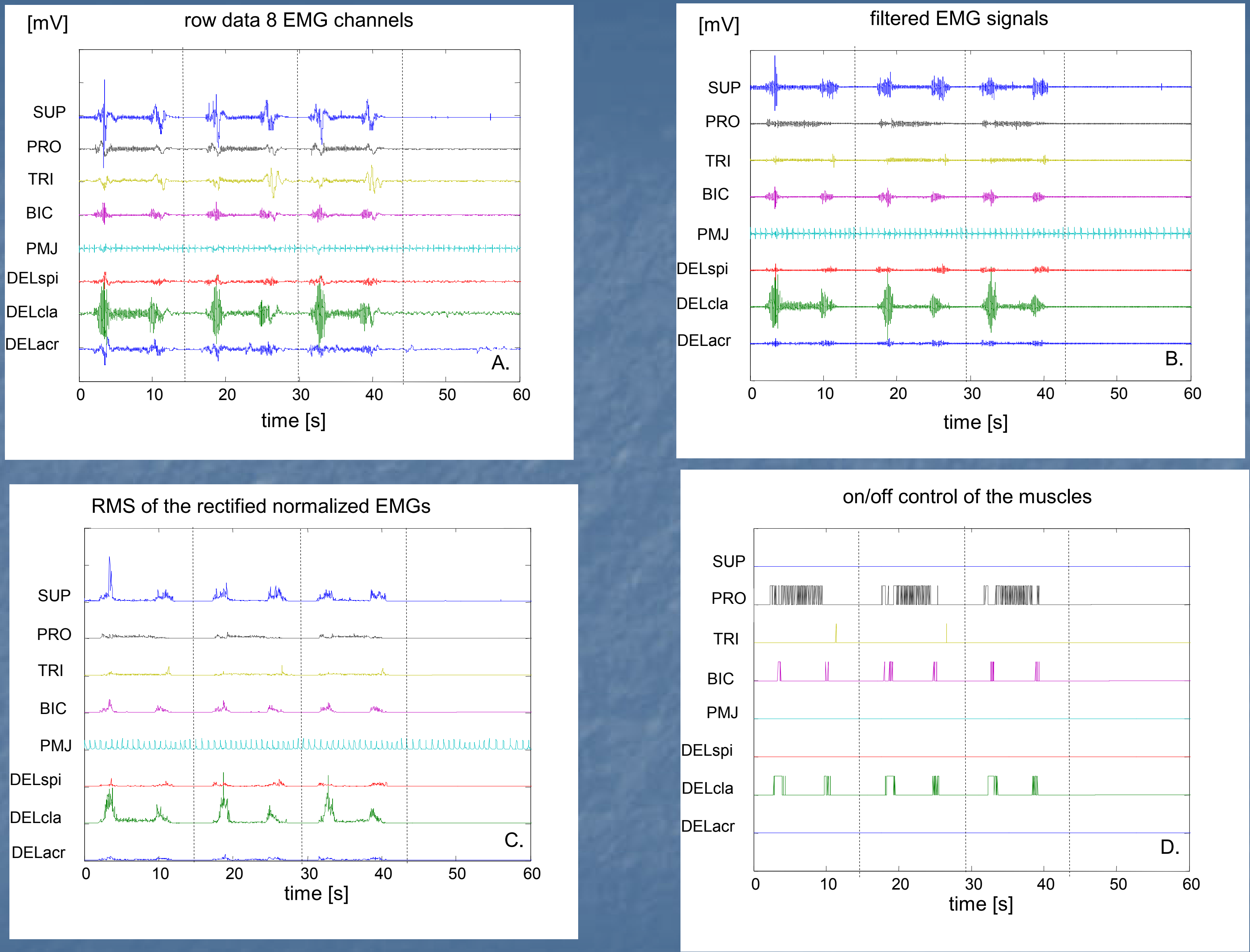
Without exoskeleton

Normalized EMGs



With exoskeleton

Three trials of elbow flexion in the sagital plane



Three trials of a reaching motor task in the sagittal plane with right hand without exoskeleton

Conclusions:

- For the muscle PMJ the heart rate is clearly visible, so a special designed filter for removing QRS complex is necessary to be developed or additional experiments have to be developed to choose suitable threshold for this muscle.
- Independently that the muscle SUP is deeply situated and covered by other muscles its EMGs is enough clear and strong and can be used as control signal for elbow supination. The muscle BRD is not so suitable for recognition of the elbow supination.
- The motor tasks and the limb positions for evoking maximal isometric contractions of the chosen muscles have to be carefully chosen.
- Better choice is to use on-off control than proportional one. It is easier to drive each motor consecutively than all together.
- Normalization of the EMG signal is necessary to be made individually for each user of the orthosis.
- Coefficient for threshold of each muscle has to be chosen carefully and special experimental justification procedure has to be developed
- Muscles PRO and SUP play significant role during motions without exoskeleton, but putting the exoskeleton they are nearly silent. Maybe other muscles performing shoulder internal/external rotation have to be investigated.

Final conclusions

- Since there are much more muscle forces than equations for joint equilibrium optimization approaches has to be applied in order to calculate muscle forces and joint reactions during different motor tasks. Problem is the objective function which has to reflect some physiological principles.
- The simplification "one muscle-one-force-one control signal" can be used where a global vision on actions of the arm is necessary.
- The motor units are really controlled by series of electrical pulses. Their number in a muscle is very big and their peculiarities are very complex.
- The electromyographic signals of surface placed muscles are a reflection of the motor unit activity and can be used for estimation of the muscle force.
- The electromyographic signal can be used after suitable processing for: estimation of the affected after diseases muscles, i.e. for diagnostic and rehabilitation purposes; for obtaining control signals for different technical devices like orthesis, prosthesis, rehabilitation robots, teleoperators, etc. after suitable processng

Some published papers describing the presented results:

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Thank you for the attention!