Upper Limb Stroke Rehabilitation: Gaming and Virtual Reality

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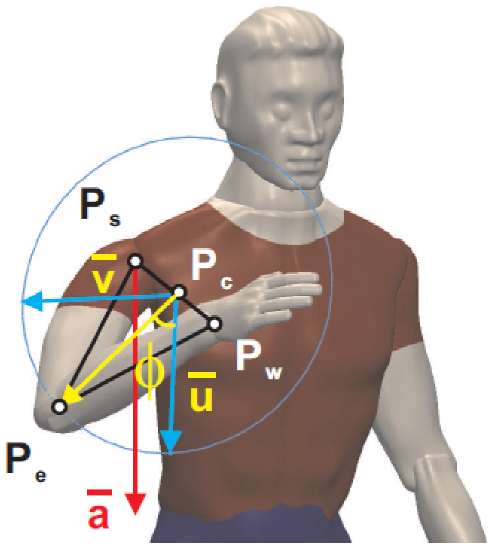
Quiz (10+2 points)

- (6 pts) How to compute swivel angle?
  - You can use your own language to describe. Not required to use equations.
- (4 pts) List two criteria for rendering natural arm postures
- (2 pts) Optional: what is Jacobian matrix augmentation?

How to compute the swivel angle?



Elbow pivot axis $\vec{\mathbf{n}}$:

$$\vec{n} = \frac{P_w - P_s}{||P_w - P_s||}$$

$\vec{\mathbf{f}}'$ is $\overrightarrow{P_e - P_c}$

$$\vec{f} = P_e - P_s$$
$$\vec{f}' = \vec{f} - (\vec{f} \cdot \vec{n}) \cdot \vec{n}$$

Reference direction $\vec{\mathbf{a}}$:

$$\vec{a} = [0, 0, -1]^T$$

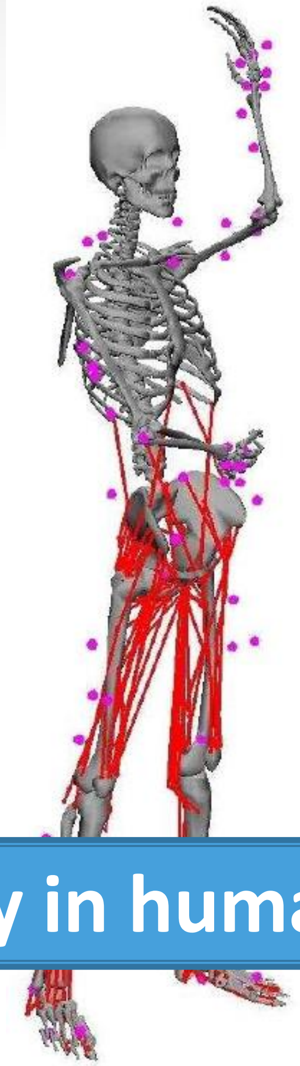
$\vec{\mathbf{u}}$ is the projection of $\vec{\mathbf{a}}$ on Plane S:

$$\vec{u} = \frac{\vec{a} - (\vec{a} \cdot \vec{n})\vec{n}}{||\vec{a} - (\vec{a} \cdot \vec{n})\vec{n}||}$$

Swivel angle ϕ:

$$\phi = \arctan(\vec{n} \cdot (\vec{f}' \times \vec{u}), \vec{f}' \cdot \vec{u})$$

What we already know …



Robot manipulator redundancy resolutions

+

Regularity in human arm motions

Robot manipulator redundancy resolution

- **Resolutions at Different Levels**

  Position, velocity, acceleration

- **General Resolution to Inverse Kinematics**

  Pseudo-inverse, general IK solver, ...

- **Task-based Resolutions**

  Jacobian matrix augmentation

- **Performance-based Resolutions**

  Various performance indices, global vs local optimization, ...

Human arm motion control

- **Motion Regularity and Variability**

  Donders' law [Donders:1848], **Fitts' law** [Fitts:54], **2/3-power law** [Terzuoloa,Viviania:80], **motion variability** [Bernstein:67], **uncontrolled manifold** [Scholz,Schoner:99]

- **Arm Motion Control Criteria**

  Energy [Tillery,Soechting:95], **motion smoothness** [Flash,Hogan:85,Suzuki,Uno:89,Kawato,Nakano:99], **task accuracy** [Harwood,Harris:99], **control complexity** [Todorov,Jordan:02]

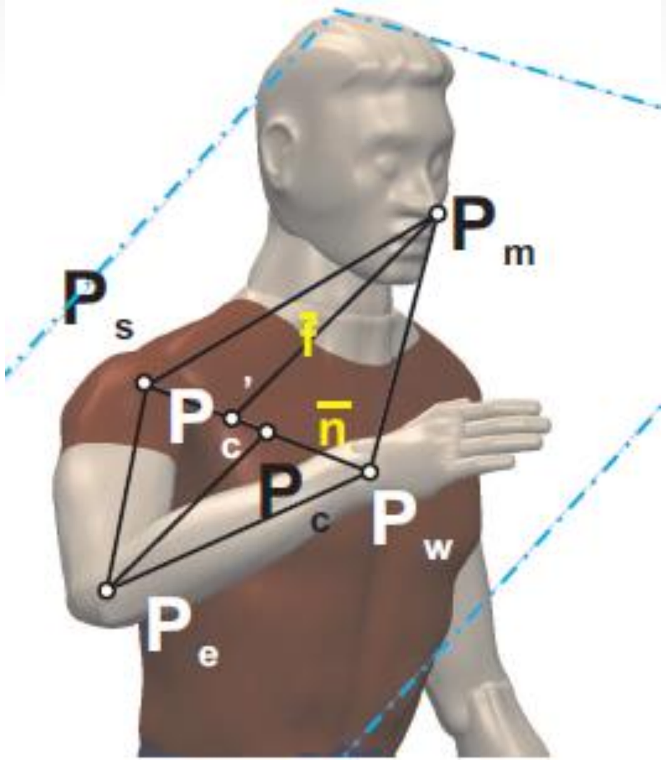
- **Criterion Synthesis**

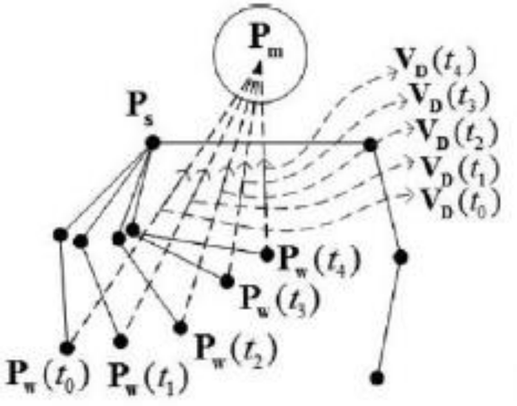
  Spatial+temporal [Biess,Flash:07]

Our goals

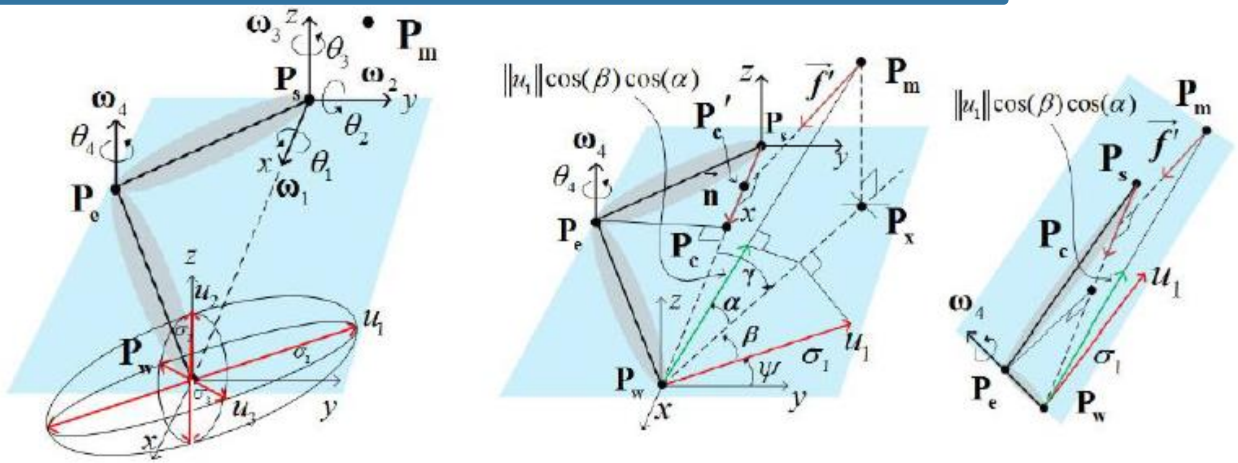
- Real-time control, unplanned motion
- Natural arm posture
- Related biological functions to behavior
  - New bio-inspired motion control criteria

Criterion 1 – Maximize Motion Effciency to Head

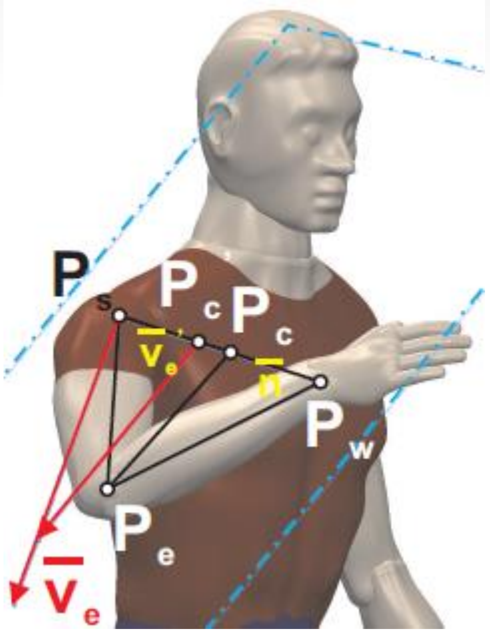


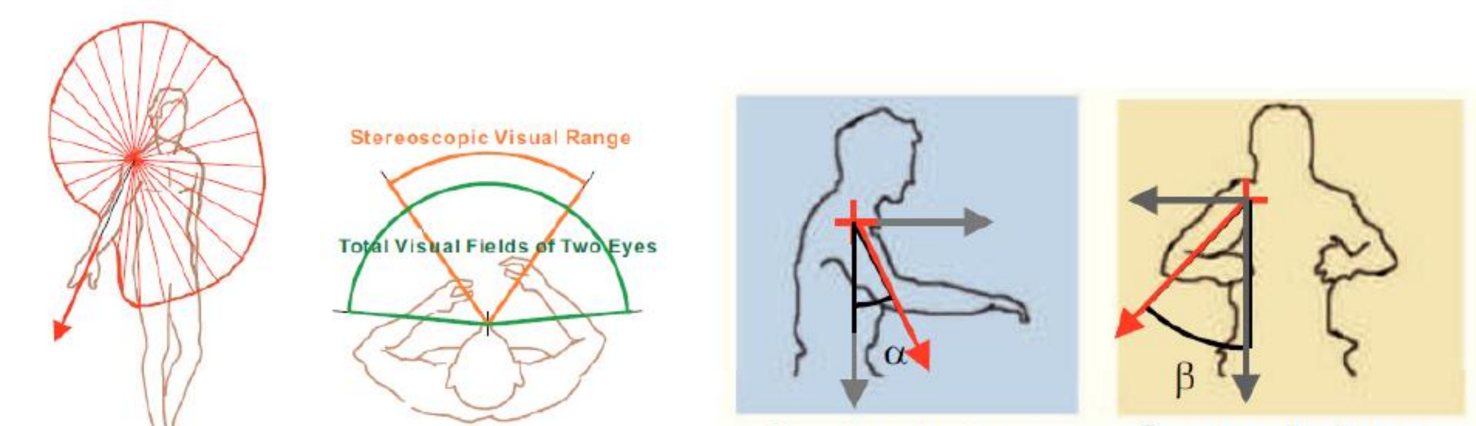


$\mathbf{P_e}$ lies on the plane of $\mathbf{P_s}$, $\mathbf{P_w}$ and $\mathbf{P_m}$:



Criterion 2 – Close to Equilibrium Arm Posture

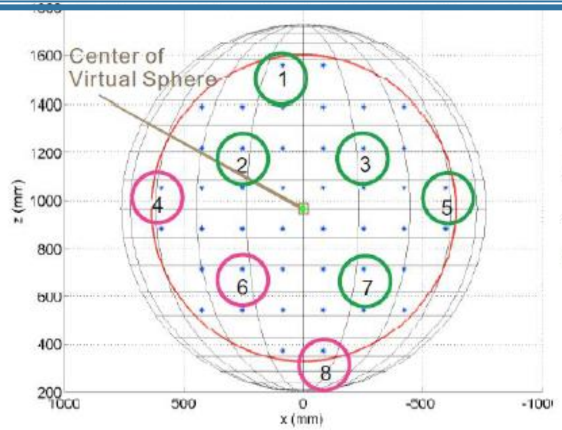


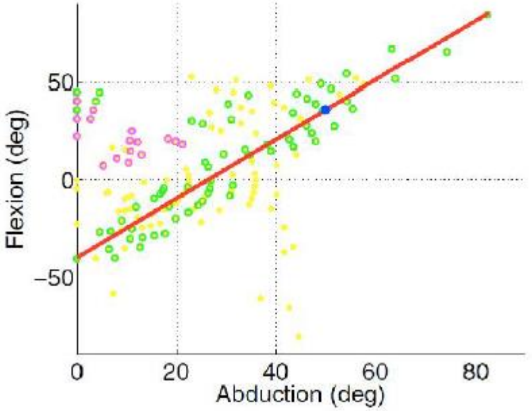


Sagittal plane

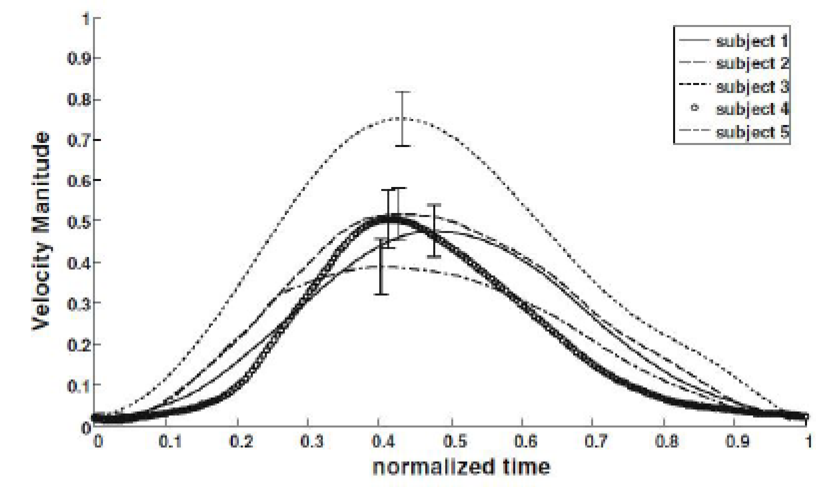
Coronal plane

$\mathbf{P}_e$ lies on the plane of $\mathbf{P}_w$ and $\vec{\mathbf{v}}_e$.





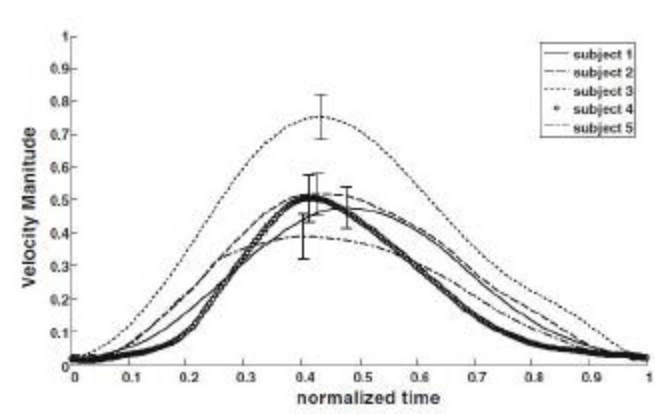
Criterion 3 – Minimize Joint Angle Change

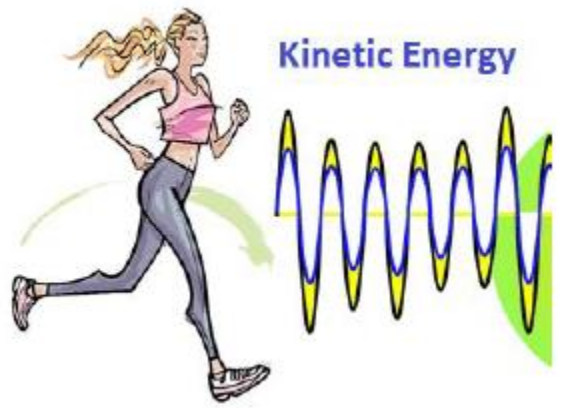


Given $\phi(k)$, $\phi(k+1) \in [\phi(k) - 0.5^\circ, \phi(k) + 0.5^\circ]$ such that:

$$\phi(k+1) = \underset{\phi'(k+1)}{\arg\min} |\vec{\theta}(k) - \vec{\theta}'(k+1)| = \underset{\phi'(k+1)}{\arg\min} \sqrt{\sum_{i=1}^{4} (\theta_i(k) - \theta_i'(k+1))^2}$$

Criterion 4 – Minimize Kinetic Energy

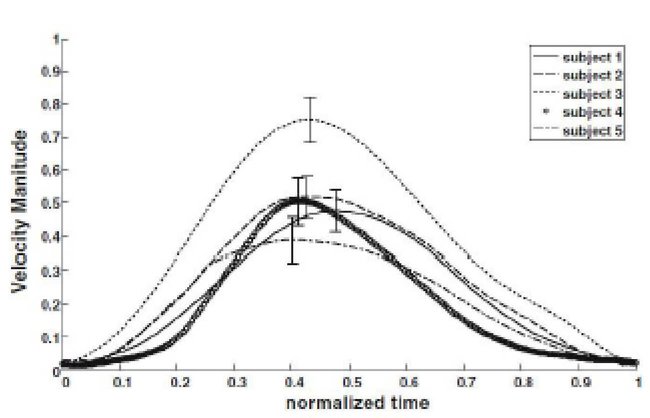


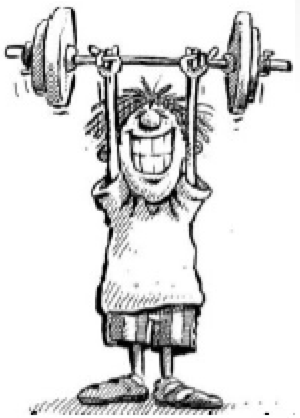


Given $\phi(k)$, $\phi(k+1) \in [\phi(k) - 0.5°, \phi(k) + 0.5°]$ such that:

$$\phi(k+1) = \arg\min_{\phi'(k+1)} |Ke(k) - Ke'(k+1)|$$

Criterion 5 – Minimize Work in Joint Space





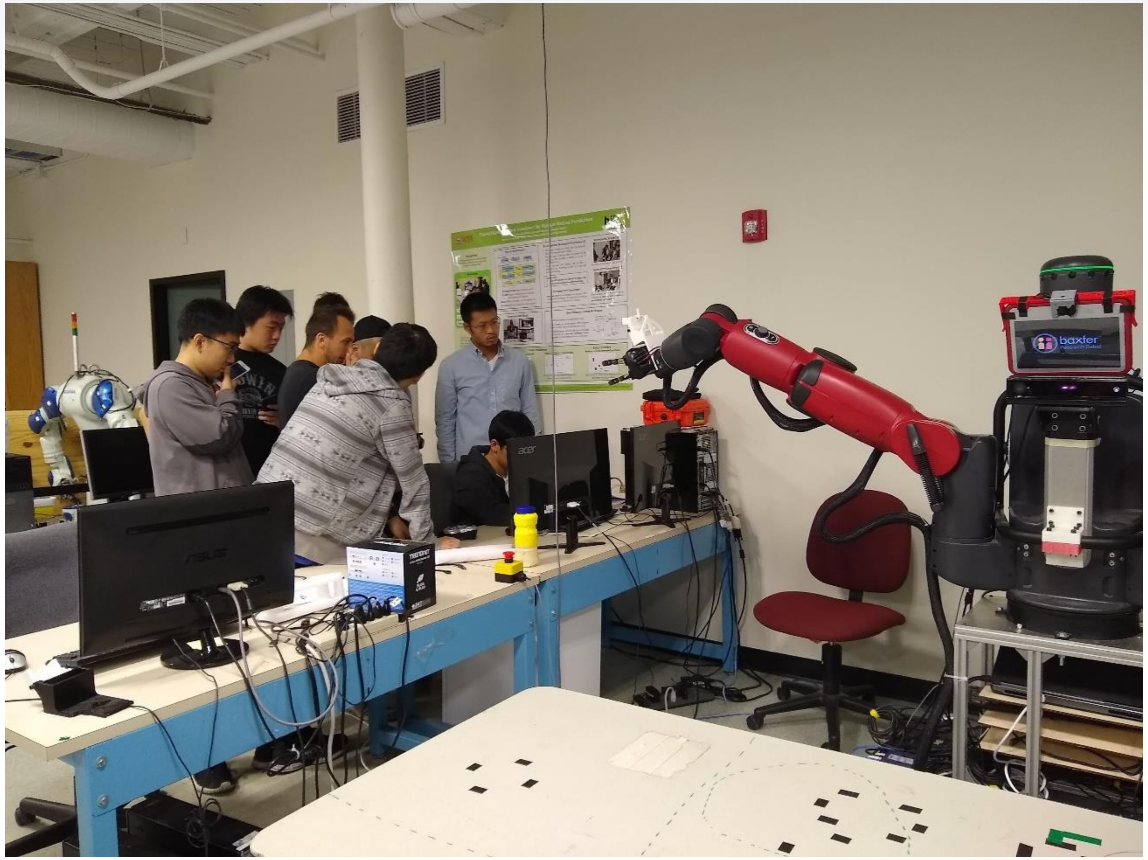
Given $\phi(k)$, $\phi(k+1) \in [\phi(k) - 0.5°, \phi(k) + 0.5°]$ such that:

$$\phi(k+1) = \underset{\phi'(k+1)}{\arg\min} |W_i|_{t_k, t_{k+1}} = \underset{\phi'(k+1)}{\arg\min} \sum_{i=1}^{4} |W_i|_{t_k, t_{k+1}}$$

Vicon & TRINA Training Session

Vicon Training

TRINA Training



Resources

- Vicon mocap system
  - Object tracking – using Tracker 3
    - https://www.youtube.com/watch?v=fpAKToBQ1hQ&list=PLxtdgDam3USXPrhGA70ix8WT_nZBLK7qB
  - Human motion tracking – using Nexus 2
    - https://www.youtube.com/watch?v=I0XjCLMD_NE&list=PLxtdgDam3USUSIeuO6UloG3ogPsFNtEJS
  - Collection of Vicon training tutorials
    - https://www.youtube.com/user/Vicon100/playlists

Resources

- Training Session
  - https://drive.google.com/drive/folders/10zwBhGY6i_KewoE7HGwJs2xUNicro-0T?usp=sharing
- Project meeting slides, including training session
  - https://drive.google.com/open?id=1eH94hnH1ZDP7RudQ2tYSc-dXaZFZd1OB
- Instructions for using Vicon, TRINA and data collection
  - https://drive.google.com/open?id=1_vpn4awJUuJ3DMsHQMCkgHTuD4gBXQTh

Synthesized Kinematic Redundancy Resolution for Natural Arm Posture Control

Further Questions

- We have so many optimization criteria
  - Which is the best?
  - Individual or blending?
  - How to combine?
  - What can we infer from the algorithm that can accurately predict arm posture?

A Framework for Comparison

- Propose methods for synthesize multiple control criteria
  - Least squares method
  - Exponential method
- Validate prediction algorithm using reaching motion data

Least Squares Method

At time step k:

$$\phi(k) = \sum_{i=1}^{5} c_i(k)\phi_i(k)$$

Linear regression:

$$\mathbf{C}(\mathbf{k}+\mathbf{1})_{5\times 1} \quad = \quad \mathbf{A}^{-1}\cdot\mathbf{b}$$

Coefficient normalization:

$$c_i(k+1) = \frac{C_i(k+1)}{\sum_{i=1}^{5} C_i(k+1)}$$

$$A = \begin{bmatrix} \phi_{c1}(k-19) & \cdots & \phi_{c5}(k-19) \\ \vdots & \ddots & \vdots \\ \phi_{c1}(k) & \cdots & \phi_{c5}(k) \end{bmatrix}_{20\times 5}$$

$$b = \begin{bmatrix} \phi_{exp}(k-19) \\ \vdots \\ \phi_{exp}(k) \end{bmatrix}_{20\times 1}$$

Exponential method

At time step k, estimation error ε_i:

$$\varepsilon_i(k) = |\phi_{exp}(k) - \phi_i(k)|$$

The inferred contribution for Criterion i:

$$C_i(k+1) = \exp[-\frac{\varepsilon_i^2(k)}{\hat{\sigma}^2(k)}]$$

Coefficient normalization:

$$c_i(k+1) = \frac{C_i(k+1)}{\sum_{i=1}^{5} C_i(k+1)}$$

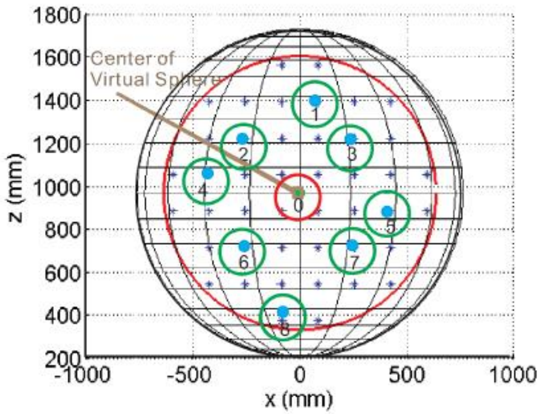
According to the **principle of maximum entropy**, the probability of the criterion i can be expressed as:

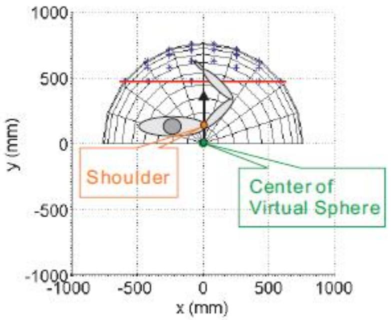
$$p_i = c \cdot exp(-\lambda \varepsilon_i^2)$$

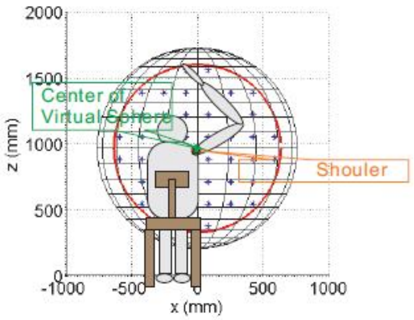
Experiment

Shoulder (P_s), elbow (P_e), wrist (P_w) position at **100 Hz**

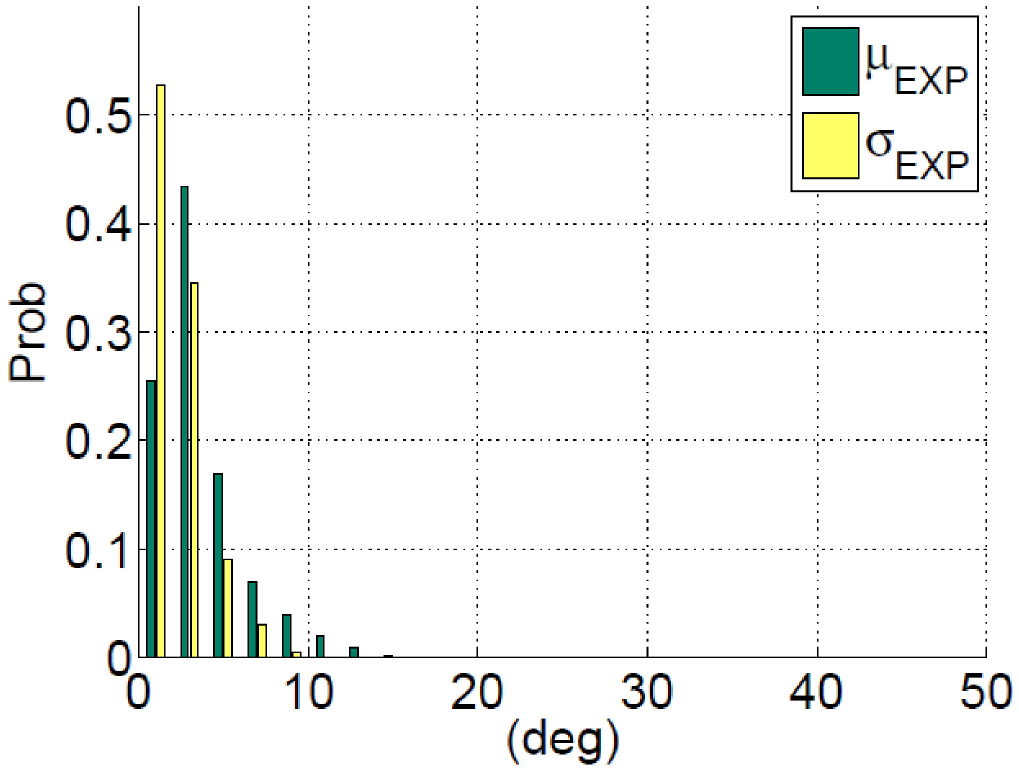
8 start points $\times$ **7 end points** $\times$ 5 **repeats** $\times$ **10 subjects** $=$ **2800 trials**



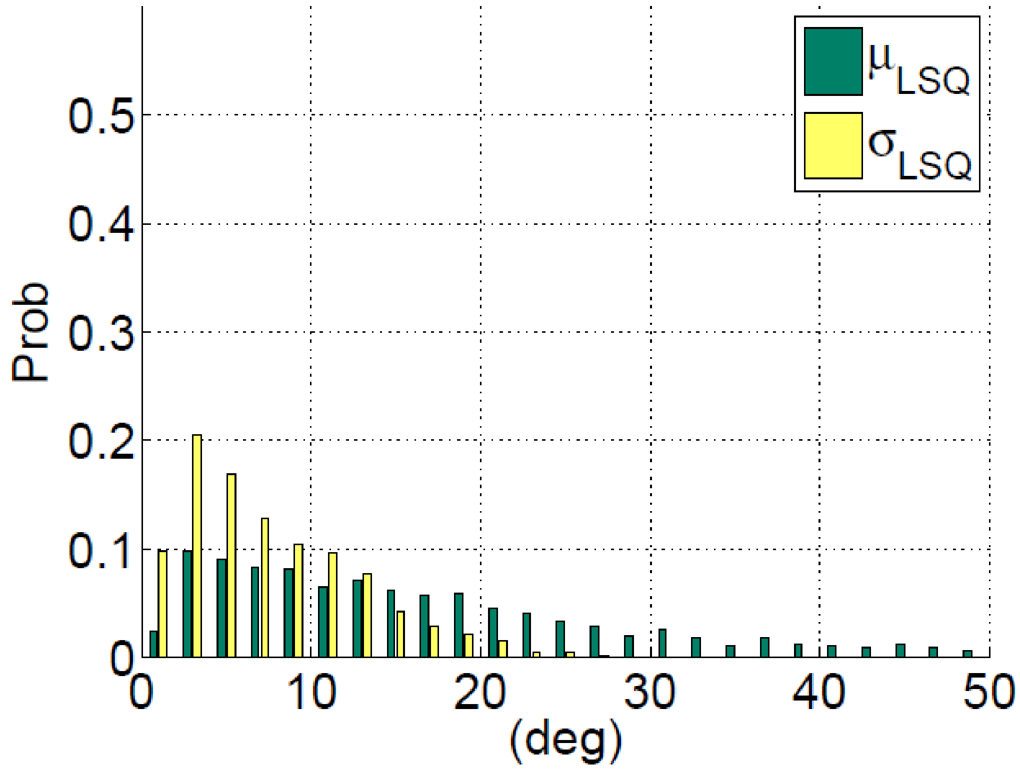




Prediction Error Distribution

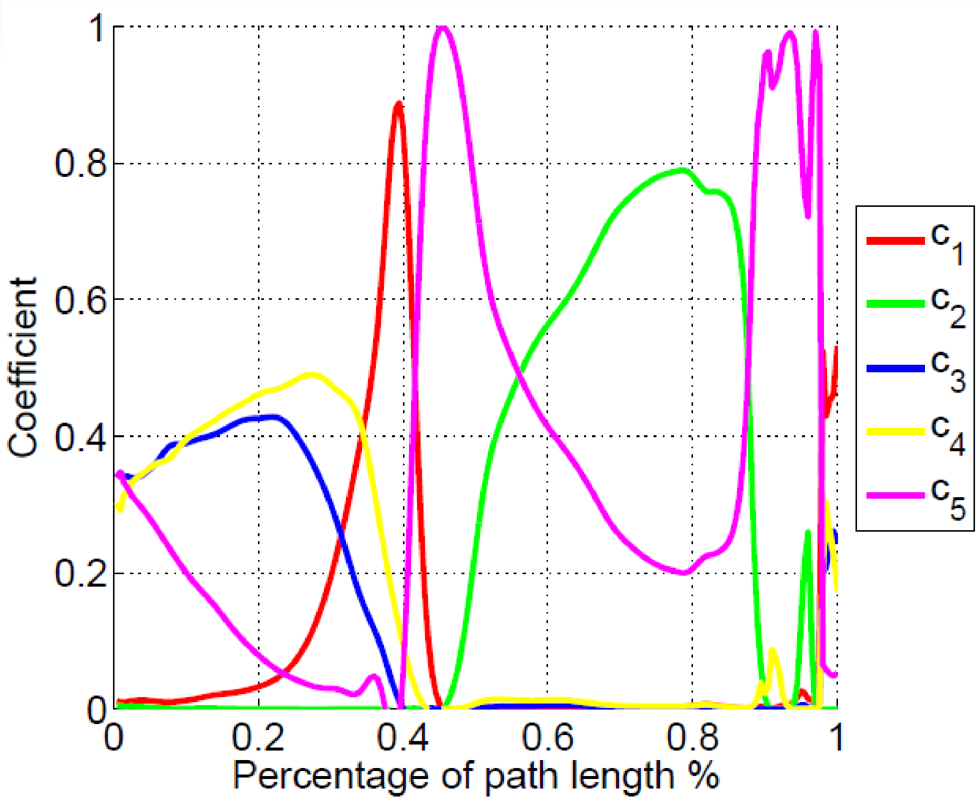


Exponential method (EXP).

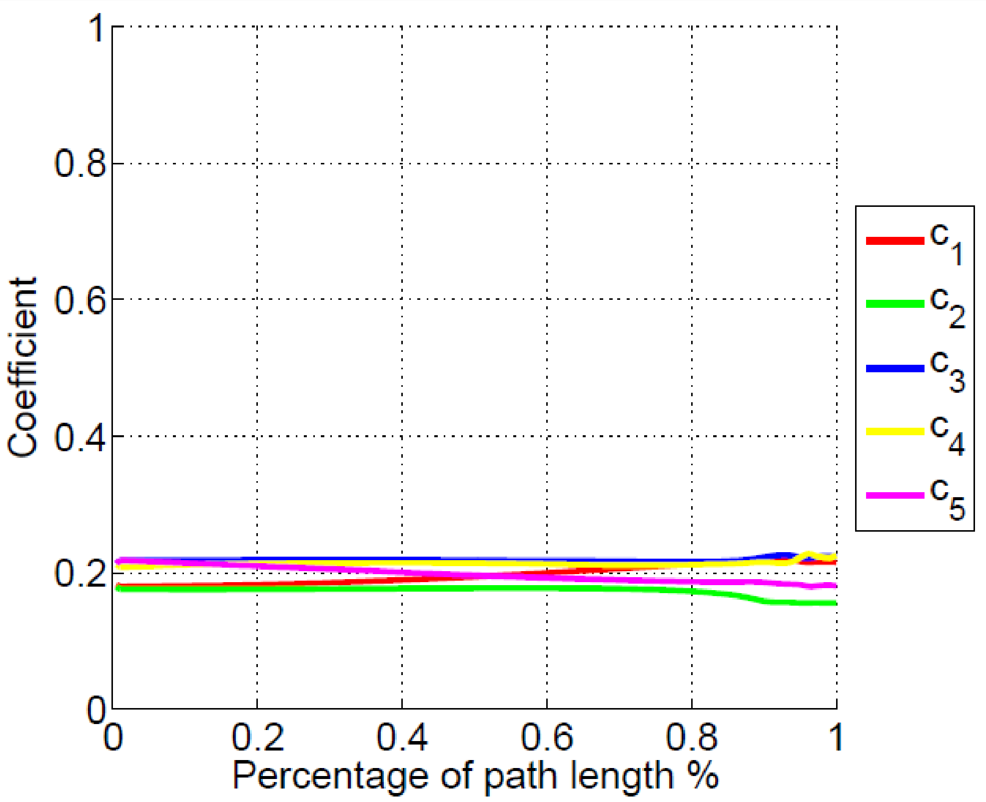


Least squares method (LSQ).

Estimated Coefficient



Exponential method (EXP).

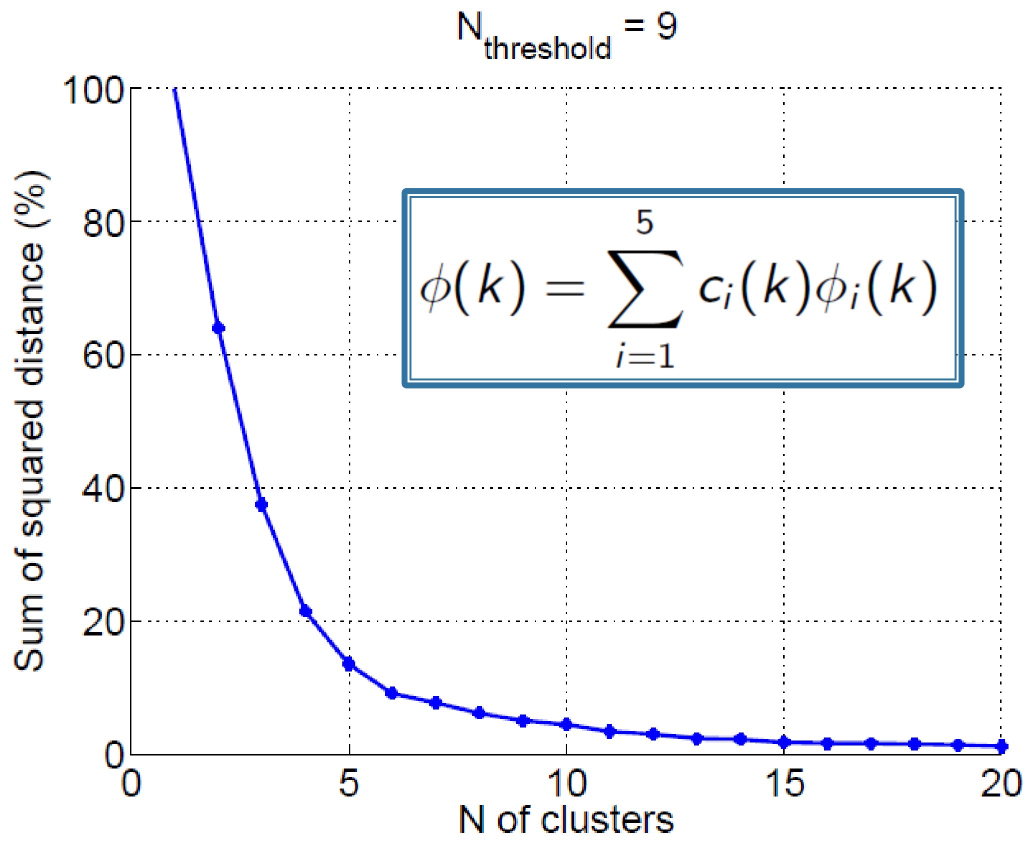


Least squares method (LSQ).

Further question

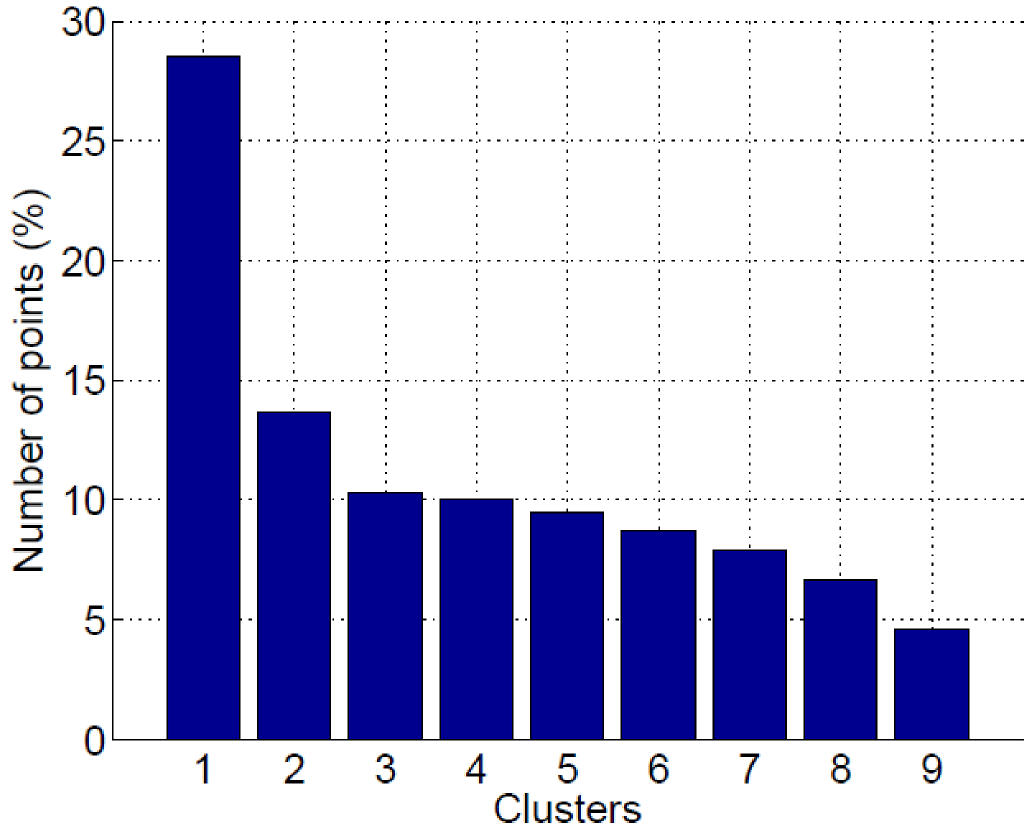
- Good prediction algorithm
  - Now we can accurately predict the arm posture of reaching motion in free space …
- Insight
  - What can we learn from the coefficients of these control criteria?
  - Unsupervised learning

Criterion Contribution Inference

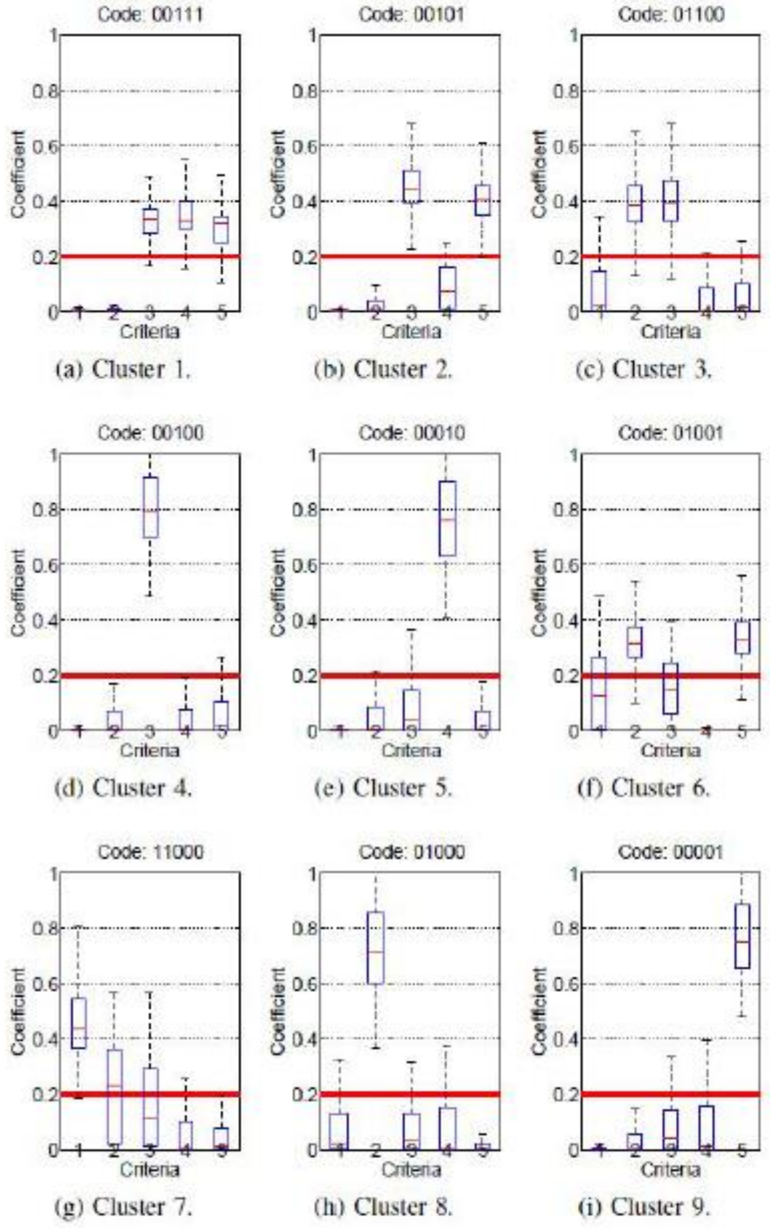


$$\phi(k) = \sum_{i=1}^{5} c_i(k)\phi_i(k)$$

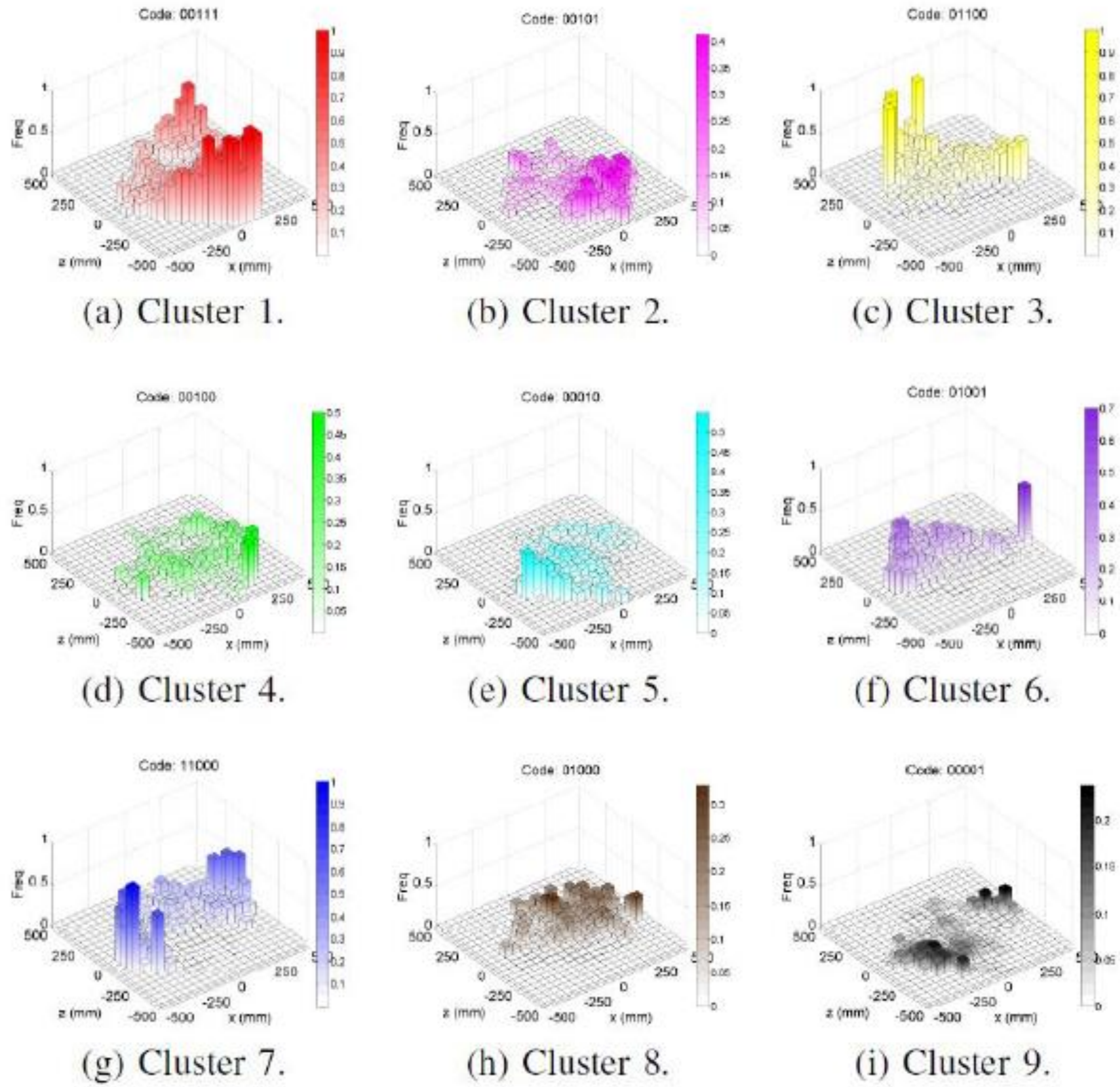
Clustering threshold.



Cluster distribution, $N = 9$.

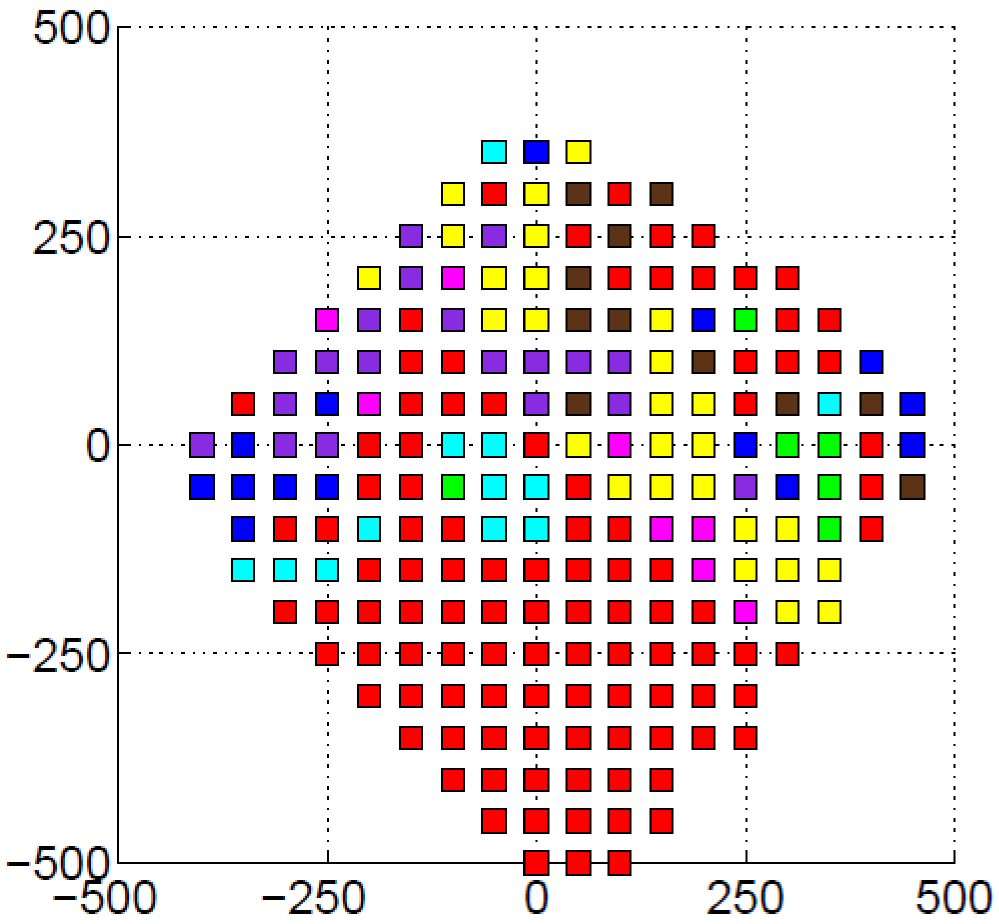


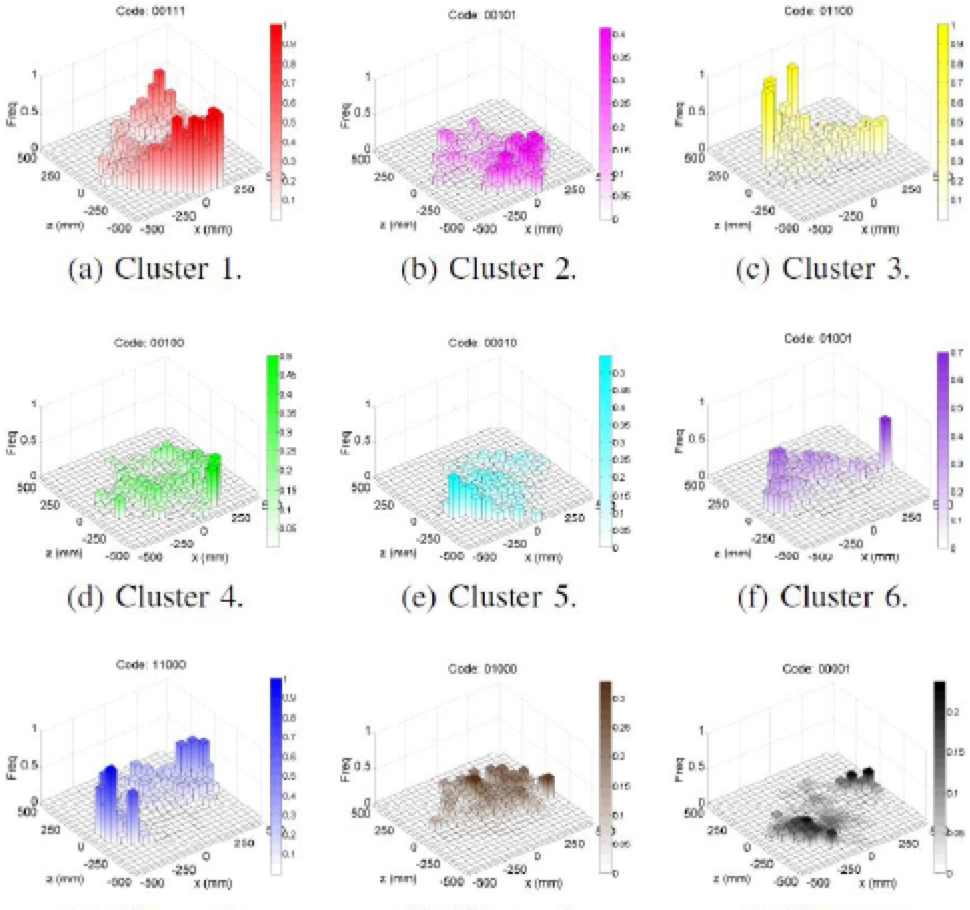
Cluster Components



Cluster Frequencies

A Spatial Map – Our insight





(a) Cluster 1. (b) Cluster 2. (c) Cluster 3.
(d) Cluster 4. (e) Cluster 5. (f) Cluster 6.
(g) Cluster 7. (h) Cluster 8. (i) Cluster 9.

Reference

- Zhi Li, Dejan Milutinovic and Jacob Rosen, “Spatial Map of Synthesized Criteria for the Redundancy Resolution of Human Arm Movements”. IEEE Transactions on Neural Systems & Rehabilitation Engineering, 23(6), pp. 1020 - 1030, Nov. 2015

Upper Limb Stroke Rehabilitation: Gaming and Virtual Reality

Why do we need games?

- Intensive therapy can recover a significant amount of lost motor control
- Video games encourage patients to practice more at home
  - Provide a motivating context
  - Provide performance feedback

Cognitive, visual and motor losses after stroke

- Memory and speech
- Unilateral neglect in Vision
  - No longer perceive one side of their visual field
- Paralysis and weakness

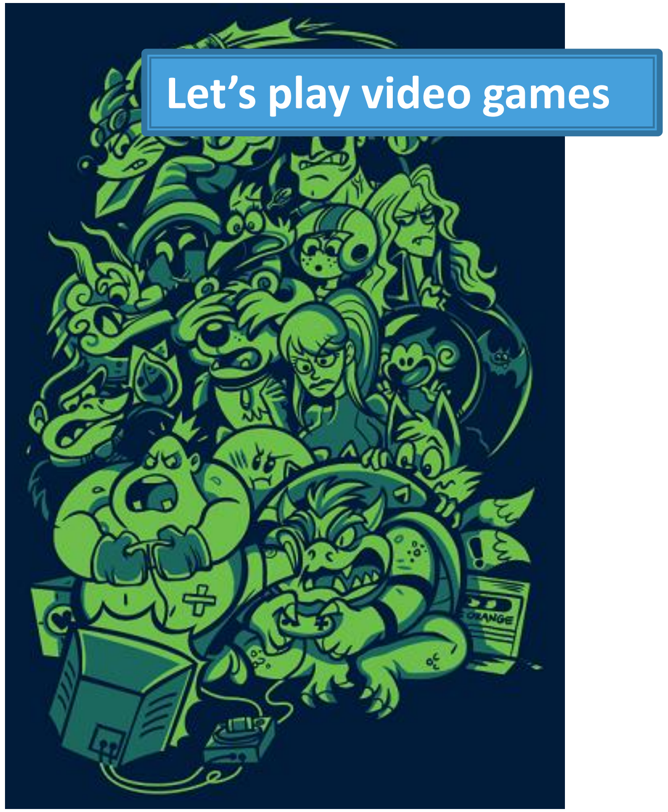
How to recover the lost function?

- Overcoming learned non-use
- Learning to use existing redundant neural pathways
- Developing new neural pathways through brain plasticity

Traditional stroke therapy

- Perform repeated motions under therapist supervision
  - Non-purposeful exercises
  - Purposeful exercises

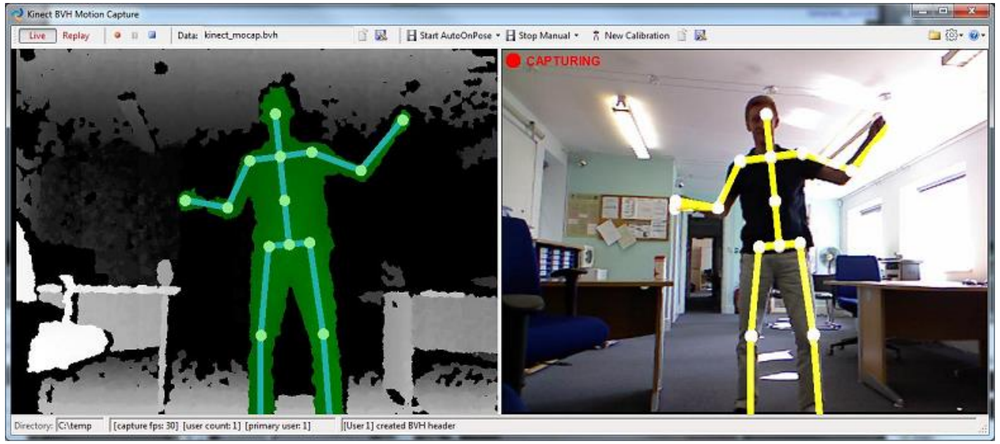
- Practice at home
  - Prescribed by therapist
  - Only 31% patients actually do it



Commercial games and consoles

Commercial games and consoles

Commercial games and consoles



Limitation of commercial games

Design customized games for stroke rehab

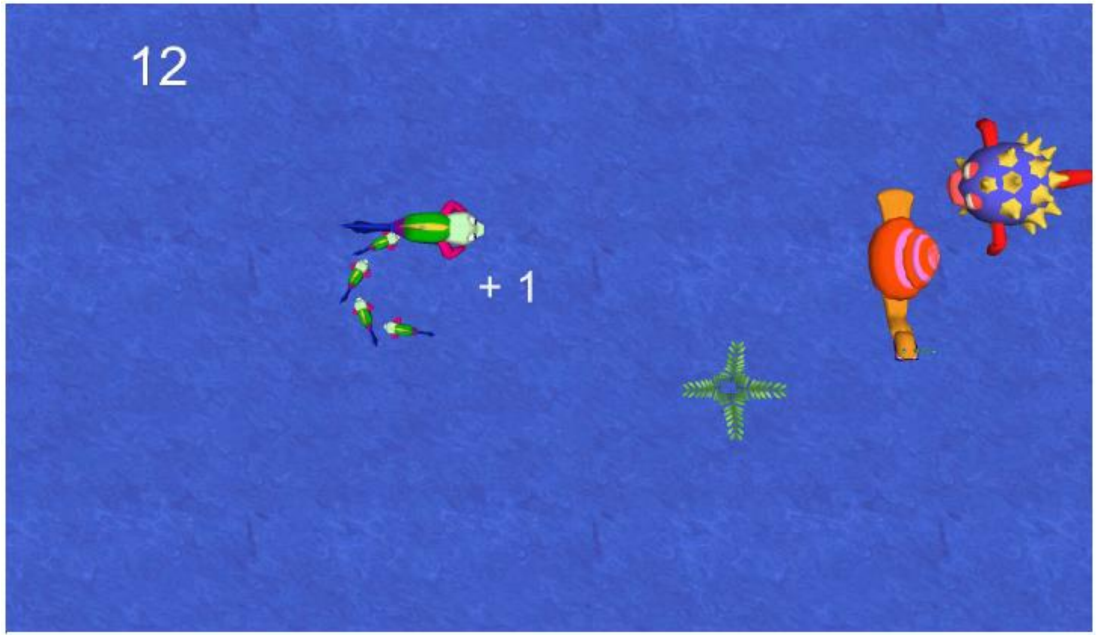
- Desired properties in stroke rehabilitation games
- Important human factors for stroke rehab games
  - Identification of the target audience, visibility and feedback
- Meaningful play and challenges
- Game design criteria
- Games that adapt to a patient’s level of recovery

Considerations in rehab game design

- Social context
  - Multi-player games provide additional motivations
  - Competitive / collaborative games
- Type of motion required
  - Single or multi-joint motions
- Cognitive challenges

Games for example

- Motor, visual and cognitive challenges



Learned Lessons in previous user studies

- How to make games playable for a broad range of stroke patients?
  - Assume no use of hands
  - Simple games should support multiple methods of user input
  - Calibrate to the patient’s motion range
  - Direct and natural mappings are necessary

Learned Lessons in previous user studies

- How to ensure that games are valuable from a therapeutic perspective?
  - Ensure that users’ motions cover their full range
  - Detect compensatory motion
  - Allow coordinated motions
  - Let therapists determine difficulty

Learned Lessons in previous user studies

- How to make games fun and challenging?
  - Audio and visuals are important
  - Automatic difficulty adjustments provide adequate challenge
  - Non-Player Characters (NPCs) and Storylines are intriguing

Kinect-based applications for stroke rehab

Limitations of Kinect-based Stroke Rehab

- Reasonable accuracy, but only for gross motions
- Unable to accurately assess internal joint rotations of shoulder
- Cannot capture rehab goals that include fine motor skills
- Not suitable for severely disabled patients