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Grasping: Insights into a redundant motor system

Jason Friedman

Macquarie Centre for Cognitive Science (MACCS)
Macquarie University, Sydney, Australia

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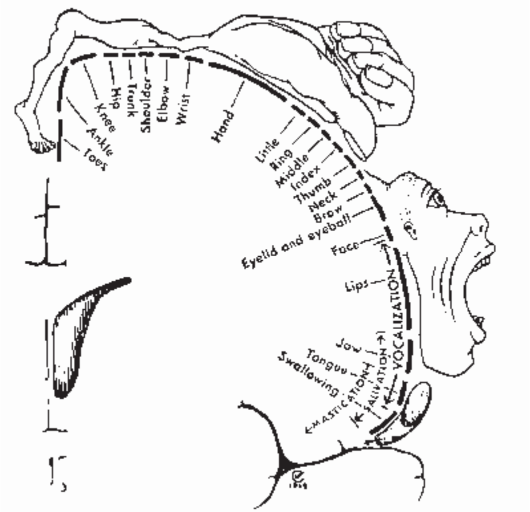
Motor homunculus

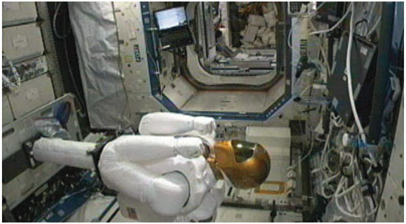
- In Penfield's homunculus, a very large area of the motor cortex is related to the hand and fingers.



What do we want to achieve?

- We can build a robot that can beat the chess grandmaster, but not a general purpose hand that can move arbitrary pieces.

What do we want to achieve?



- The R2, the most advanced humanoid arm, has 12 degrees of freedom in the hand, and 350 sensors
- Despite this, it cannot perform dextrous manipulation
- It is currently on the international space station!

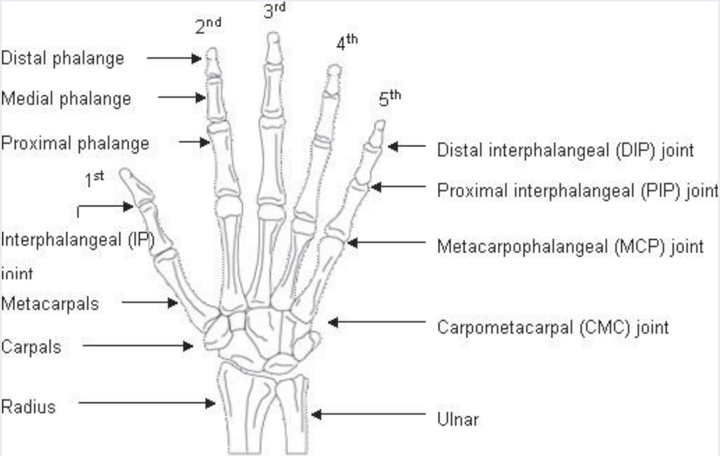
Redundancy in grasping

- Redundancy = more solutions than necessary
- When grasping, we are required to solve (at least) these mostly redundant problems:
    - Select grasp points for a particular task
    - Select the posture of the hand
    - Select the stiffness properties of the fingers and grasp
    - Coordinate the grip and tangential forces of the fingers
    - Share the force produced by multiple fingers
- and ideally do this in an efficient / optimal way

Degrees of freedom problem

There are many degrees of freedom in the hand

$>$ 20 joints



Large number of muscles

Experiments

I will present the results of three studies looking at different aspects of redundancy in grasping:

1. Grasp selection - from all possible grasps (fingertip locations, hand postures), which grasps do we select for object manipulation?
2. Control of load and grasp forces - how do we coordinate finger forces to stabilise and manipulate an object?
3. "Good" and "bad" variance - what is the relation of good and bad variance to frequency?

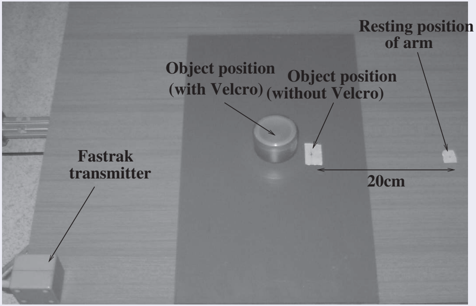
Experiment 1: Which grasps do we select for object manipulation?

Friedman & Flash, *Cortex*, 2007

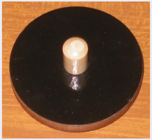
- We need to select posture and impedance properties to successfully perform the manipulation

- This work examined the grasp selected at the start of the manipulation rather than the movement

Experimental setup



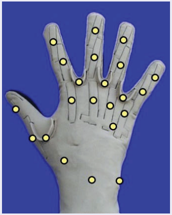
Objects

Experiment 1: Methods
Friedman & Flash, *Cortex*, 2007

Kinematic recording

Joint angles recorded with the CyberGlove, position and orientation of the wrist recorded with the Fastrak



Stiffness recording

Forces applied to each finger using the CyberGrasp

Grasp Jacobian
Friedman & Flash, *Cortex*, 2007

Relationship between joints, contacts and object

The grasp Jacobian is the transformation from the joint velocities to the velocity of the object being grasped. It takes into account the contact relationships between the fingers and the object.

$$
\begin{tikzcd}
\text{Joints} & \text{Contacts} & \text{Object} \\
\dot{\theta} \arrow[r, "J_h"] \arrow[rr, bend left, "G_h"] & \dot{x}_c & \dot{x}_o \arrow[l, "G^T"'] \\
\tau & f_c \arrow[l, "J_h^T"] \arrow[r, "G"] & F_o \arrow[ll, bend left, "G_h^{-1}"]
\end{tikzcd}
$$

Experiment 1: Results - Jar lid

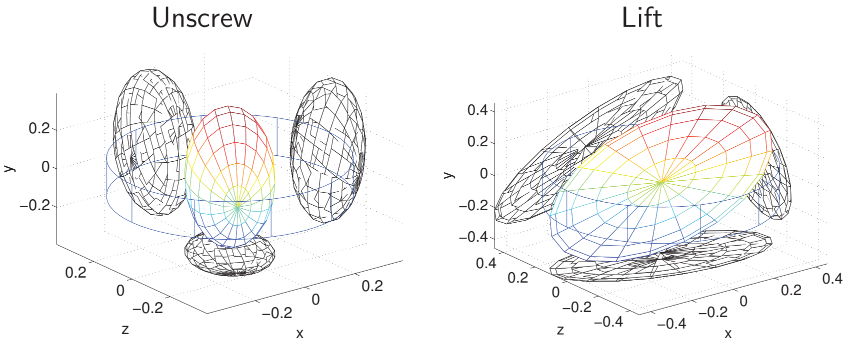
- What are the task requirements for unscrewing the lid of a jar, or lifting the lid of a jar

,,

- The grasp Jacobian can be visualised as an ellipsoid (its shape and orientation will depend on the posture of the hand)
- In order to most efficiently perform the task, the ellipsoid should be aligned with the requirements of the task.

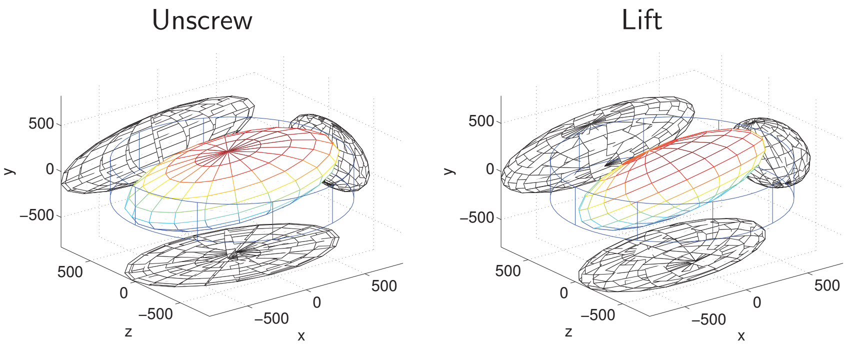
Experiment 1: Results (Jar lid - torque)

Friedman & Flash, *Cortex*, 2007



- When unscrewing, the major axis of the torque ellipsoid was generally closely aligned with the axis of rotation (y).
- A larger torque about the vertical (y) axis can be generated using the unscrew grasp compared to the lift grasp.

Experiment 1: Results (Jar lid - stiffness)
Friedman & Flash, *Cortex*, 2007

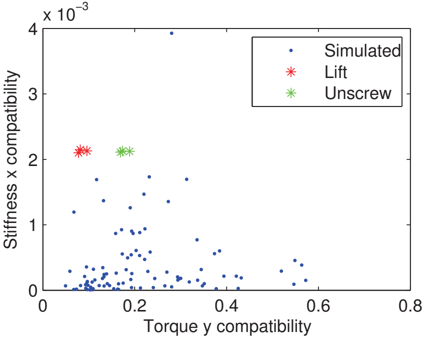


- More isotropic translational stiffness ellipsoids are observed for picking up the lid.
- x and z stiffness is greater than in the y direction, the direction of motion.

Experiment 1: Results (Optimal grasp selection)

Friedman & Flash, *Cortex*, 2007

- How do we combine two different requirements (desired torque ability, and desired stiffness)?
- We randomly generated a large number of grasps and computer their torque ability and stiffness
- It seems that subjects chose the highest torque compatibility is selected, given that the stiffness is high.



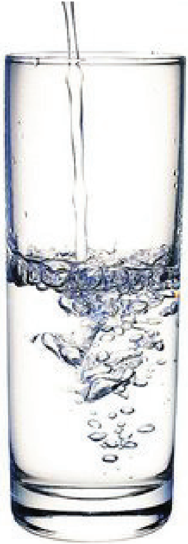
Experiment 1: Conclusions
Friedman & Flash, *Cortex*, 2007

Conclusions

- Despite the redundancy of the system, invariant features were observed across subjects in terms of the capabilities of the grasp, which are related to the task requirements.
- It seems that the selected postures for some tasks were close to "optimal" for maximizing torque / force production capability under stiffness constraints.

Experiment 2:Control of grip and load forces

Friedman, Latash & Zatsiorsky, *Exp Br Res*, 2009



- When holding a glass, we need to apply vertical *load forces* to act against gravity, and horizontal *grip forces* to prevent slipping.
- We also need to stop the object from rotating
- This is a redundant problem - how do we share the forces among the fingers?
- How do we deal with this problem in a dynamic situation, for example, holding a glass that is being filled with water (or liquid of your choice)?

Experiment 2:Control of grip and load forces

Friedman, Latash & Zatsiorsky, *Exp Br Res*, 2009

What must a grasp satisfy? (Physics)

1. The sum of the tangential forces of the fingers must equal the load force:

$$-L = F^t_{th} + F^t_{VF}$$

2. The static external moment M_{st} should be equal and opposite to the applied moment

$$-M_{st} = F^n_{th} d^n_{th} + F^n_{VF} d^n_{VF} + F^t_{th} d^t_{th} + F^t_{VF} d^t_{VF}$$

3. The sum of the normal forces should equal zero

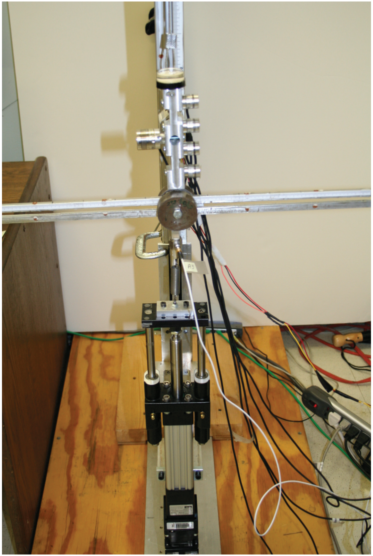
$$0 = F^n_{th} + F^n_{VF}$$

4. ~~The sum of the normal forces should equal zero~~

$$\xcancel{0 = F^n_{th} + F^n_{VF}}$$

Experiment 2:Statement of the problem

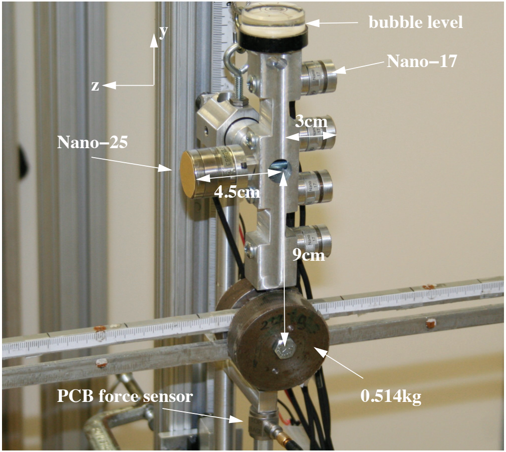
Friedman, Latash & Zatsiorsky, *Exp Br Res*, 2009



- This setup models grasping a cup being filled with water.
- For a pinch grasp (thumb and index finger), the grip force applied by the fingers increases linearly with an increase in the load force (Johansson & Westling, 1984).
- How will the grip force change when grasping with five fingers?

Experiment 2:Statement of the problem

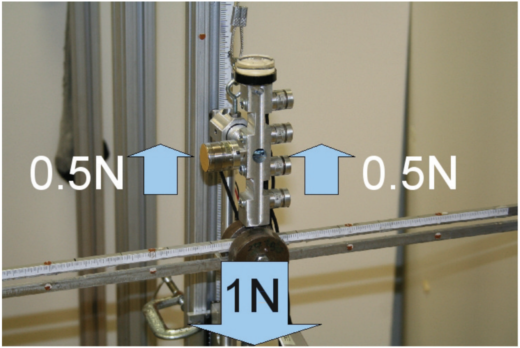
Friedman, Latash & Zatsiorsky, *Exp Br Res*, 2009



- In this setup, the moment arms (distance from centre of mass to grip points) is unequal for the thumb and other fingers.
- Hence, simply scaling the forces will not maintain rotational equilibrium.
- There are (at least) two possible solutions:

Experiment 2:Balance of moments - strategy 1

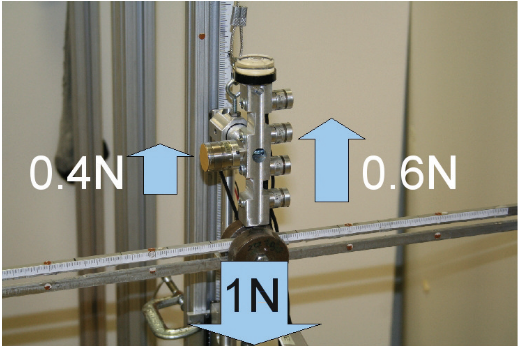
Friedman, Latash & Zatsiorsky, *Exp Br Res*, 2009



- Share the load forces evenly between the thumb and virtual finger
- However, this will produce a moment and cause the handle to rotate
- A moment in the opposite direction must then be produced by changing the sharing pattern of the grip forces

Experiment 2:Balance of moments - strategy 2

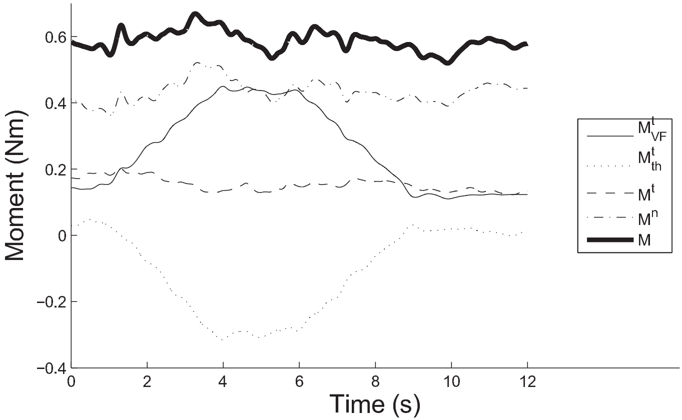
Friedman, Latash & Zatsiorsky, *Exp Br Res*, 2009



- Produce more of the load force with the virtual finger (0.6 to 0.4)
- This will not produce a moment from the load forces
- So do not need to alter the moment from the normal forces, rather can use the same sharing pattern for the normal forces

Experiment 2:Results

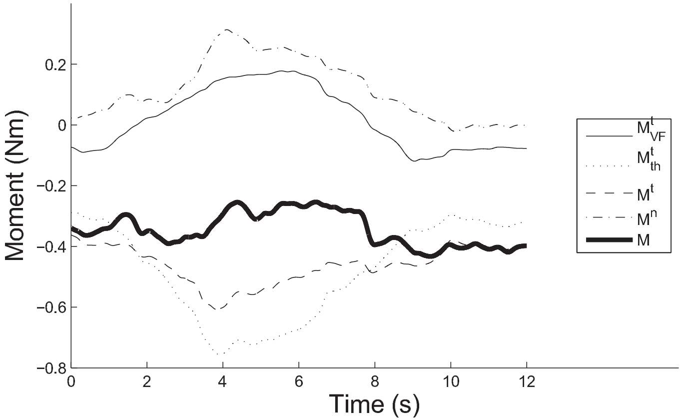
Friedman, Latash & Zatsiorsky, *Exp Br Res*, 2009



- Most of the subjects used the second strategy

Experiment 2:Results

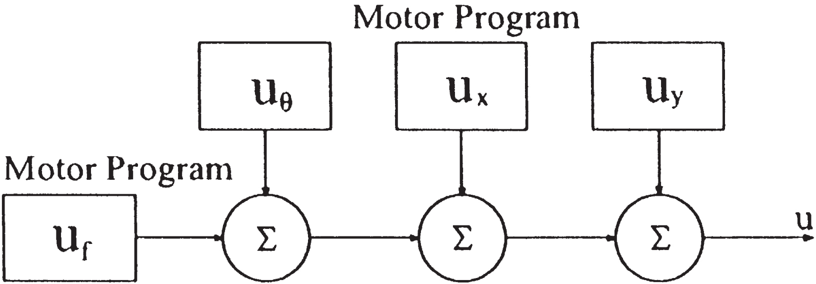
Friedman, Latash & Zatsiorsky, *Exp Br Res*, 2009



- A small number of subjects used the first strategy

Friedman, Latash & Zatsiorsky, *Exp Br Res*, 2009

- The principle of superposition is that some actions can be decomposed into elemental actions that can be independently controlled.
- Systems that implement this principle are advantageous, because they are computationally simpler.



Experiment 2: Superposition

Friedman, Latash & Zatsiorsky, *Exp Br Res*, 2009

- If elemental variables (e.g. load and grip forces of the fingers, moments) have low correlations, this suggests that they are controlled independently.
- If elemental variables have high correlations, this suggests that they may be controlled together.
- This can be tested using principal component analysis (PCA) with varimax rotation on the detrended data within a trial.

Experiment 2: Superposition

Friedman, Latash & Zatsiorsky, *Exp Br Res*, 2009

- Three independent sets can be observed:
  1. F^t_{th} and M^t_{th}
  2. F^t_{VF}, M^t_{th} and M^n_{VF}
  3. F^n_{th} and F^n_{VF}
- Note that F^n_{VF} and M^n_{VF} are in *different* sets

Variable	PC1	PC2	PC3
F^t_{th}	**0.71**	0.00	0.00
F^t_{VF}	0.02	-**0.60**	-0.05
F^n_{th}	0.00	0.01	-**0.70**
F^n_{VF}	0.01	0.00	**0.70**
M^t_{th}	-**0.71**	0.00	0.00
M^t_{VF}	0.02	-**0.60**	-0.05
M^n_{VF}	0.03	-**0.53**	0.12

Experiment 2: Conclusions

Friedman, Latash & Zatsiorsky, *Exp Br Res*, 2009

- Two different strategies are used to achieve rotational stability when grasping the object while a load is applied.
- Superposition appears to be used, this allows the neural controller to parition the task and independently control the components.

Experiment 3: Relation of "Good" and "bad" variance to frequency

Friedman, SKM, Zatsiorsky & Latash, *Exp Br Res*, 2009

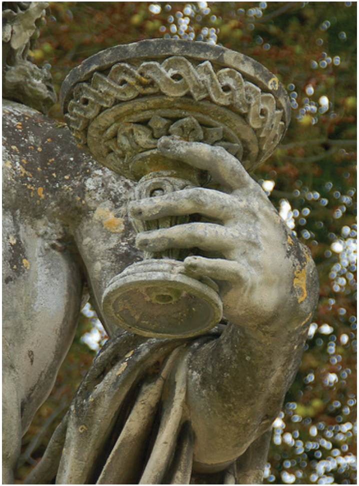
- When there are multiple effectors in a redundant task, how can we stabilise the output?
- Coordination of the covariance between the effectors can allow us to take advantage of the redundancy.

Experiment 3:Prehension synergies

Friedman, SKM, Zatsiorsky & Latash, *Exp Br Res*, 2009

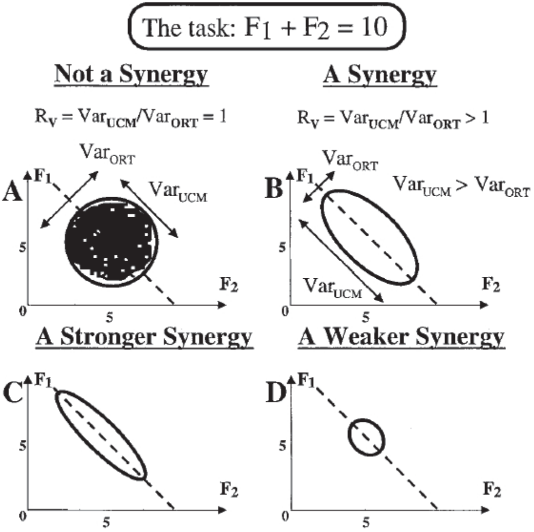
A *prehension synergy*

- is a conjoint change of finger forces and moments during multi-finger prehension tasks
- adjusts to changes in task parameters
- compensates for external or self-inflicted disturbances



Experiment 3:Uncontrolled Manifold (UCM)

Friedman, SKM, Zatsiorsky & Latash, *Exp Br Res*, 2009



Experiment 3:Uncontrolled Manifold (UCM)

Friedman, SKM, Zatsiorsky & Latash, *Exp Br Res*, 2009

- The *uncontrolled manifold* approach (Scholz and Schöner, 1999) can be used to explain the variance observed when a given task has more degrees of freedom than necessary.
- It assumes that the neural controller wants to stabilize a particular *performance variable*.
- This can be achieved by selecting a subspace such that within the subspace, the value of the performance value is unchanged.
- This subspace is known as the *uncontrolled manifold*, because selecting different values within this manifold will not change the desired performance variable.
- Then the variance that does not change the performance variable (V_{UCM}) and variance that does change the performance variable (V_{ORT}) can be calculated.

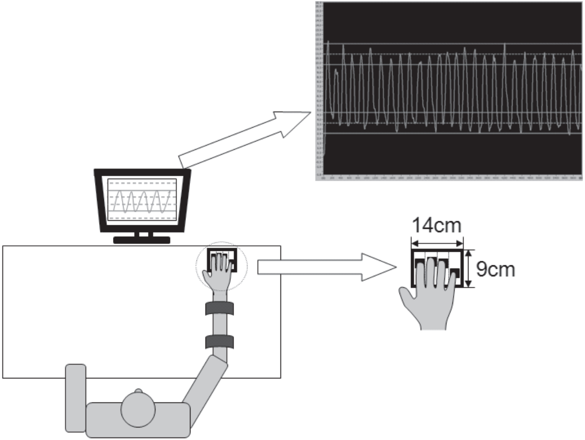
Experiment 3: Expected variance components

Friedman, SKM, Zatsiorsky & Latash, *Exp Br Res*, 2009

- In previous studies, it has been observed that:
  1. V_{UCM} ("good variance") is proportional to F
  2. V_{ORT} ("bad varaince") is proportional to $\frac{dF}{dt}$
- Question: In a cyclic task, is V_{ORT} due to frequency or $\frac{dF}{dt}$?

Experiment 3: Experimental methods

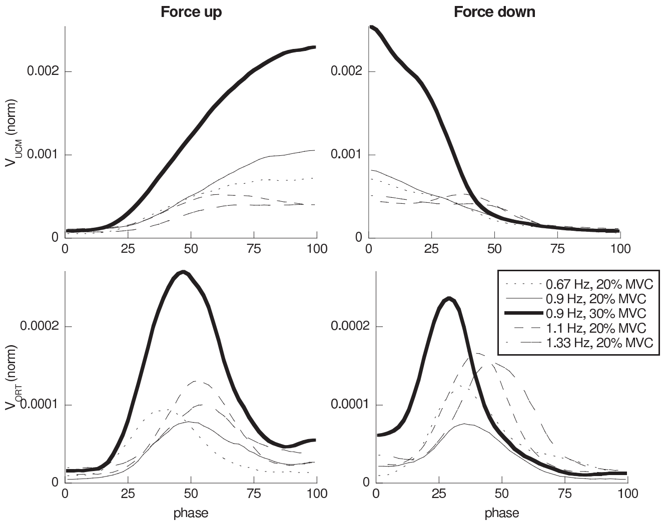
Friedman, SKM, Zatsiorsky & Latash, *Exp Br Res*, 2009



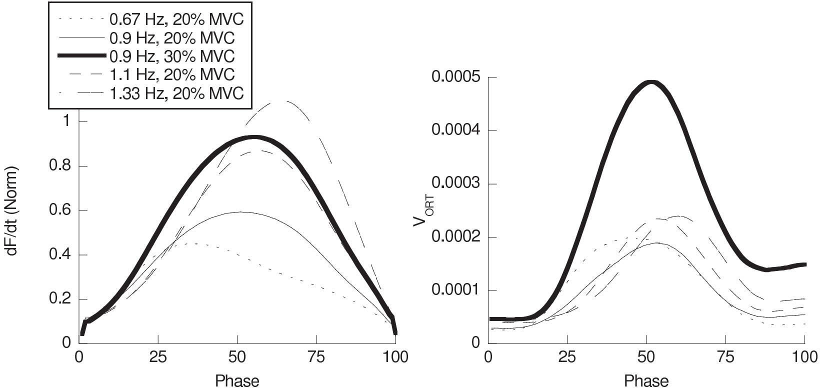
- The subjects had to press with all four fingers, and produce a sinusoidal force, between given targets, and with a certain timing (using a metronome)
- Feedback on the *total force* of the four fingers was shown on a monitor.

Experiment 3: Results

Friedman, SKM, Zatsiorsky & Latash, *Exp Br Res*, 2009



- As expected, V_{UCM} increased approximately linearly with the force
- V_{ORT} increased linearly with the force rate (dF/dt)



- However, while within a trial V_{ORT} is proportional to dF/dt, as the frequency increases (and hence so does dF/dt), V_{ORT} *does not* increase.

Experiment 3: Conclusions

Friedman, SKM, Zatsiorsky & Latash, *Exp Br Res*, 2009

- Within a trial, F was proportional to V_{UCM}, $\frac{dF}{dt}$ to V_{ORT}.
- Across trials, at the same amplitude, V_{ORT} did not increase as the frequency and $\frac{dF}{dt}$ increased.
- It seems that the "bad" variance (V_{ORT}), which is related to timing errors, is modulated to keep the errors in performance at an acceptable level, perhaps by increasing the timing accuracy.

General conclusions

- Redundancy is observed at many levels in the planning and production of movement / forces, such as:

Posture selection

- Which hand posture / grasp points do we select to perform a particular manipulation?

- The high level of redundancy allows us to optimize multiple requirements, while grasping the same object.

Force sharing in grasping

General conclusions

- Open questions (that interest me):
  - How does the CNS select almost instantaneously near-optimal postures for grasping novel objects?
  - Can we learn to grasp objects by observation / imitation, and what information do we use to do this?
  - What is the mechanism for sharing forces between the fingers during grasping? Is it mostly mechanical?
  - How is hierarchical control achieved in the motor system, and how do we know it if we see it?
  - Can superposition be observed in more complex motor tasks?
  - How does the CNS negatively covary forces in order to stabilise a performance variable?
  - If it is capable of tuning this covariation due to frequency, why is more accurate performance not possible?

Thanks

- Experiment 1 was performed at the Moross laboratory at the Weizmann Institute of Science, Israel, as part of my PhD studies, under the supervision of Prof. Tamar Flash.
- Experiments 2 and 3 were performed in the Biomechanics and Motor Control laboratories at the Pennsylvania State University, USA, in the labs of Prof. Mark Latash and Prof. Vladimir Zatsiorsky. Experiment 3 was performed together with Varadhan SKM.