Human hand grasping from a robotics perspective

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Workshop on Grasp Acquisition: How to Realize Good Grasps @ RSS 2010

Outline

- Grip (internal) forces control and torque minimization
- Grip forces and Transcranial Magnetic Stimulation
- Grip forces, grasp control end synergies

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- G. Baud-Bovy, D. Prattichizzo, N. Brogi. Does torque minimization yield a stable human grasp?. In Multi-Point Physical Interaction with Real and Virtual Objects, F. Barbagli, D. Prattichizzo, K. Salisbury (eds.), STAR, Springer Tracks in Advanced Robotics, Springer, 2005.
- G. Baud-Bovy, D. Prattichizzo, S. Rossi. Contact forces evoked by transcranial magnetic stimulation of the motor cortex in a multi-finger grasp. Brain Research Bullettin, Special Issue on Robotics and Neuroscience, 75(6):723-736, 2008.
- D. Prattichizzo, M. Malvezzi, A. Bicchi. On motion and force controllability of grasping hands with postural synergies. Robotics Systems Science 2010.

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- **Grip (internal) forces control and torque minimization**
- Grip forces and Transcranial Magnetic Stimulation
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Robotic methodologies to study hands

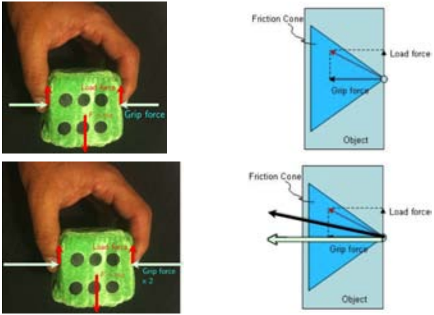
Robot model → Hand motion/forces

Internal model → Hand motion/forces

Control schemes and internal models

- How does the motor system control finger forces?
- Theoretical issues involved in controlling real or artificial hands are similar.
- Control schemes can be divided into two categories:
- Feedback control schemes:
  - Feedforward (predictive) control schemes:
  - Requires internal models to predict
- Johansson, Cole (1994) Can. J Physiol. Pharmacol., 72:511-524 *The existence of a coupling between grip and load force demonstrates that the motor system uses an internal model to control grip force*
- Internal models for grasping are physically based and contain information on object (weight, coefficient of friction) and environments properties

Grip force choice in pinch grasp



- Minimize (muscle) energy expenditure
- Maximize the grasp stability (constraint violation)
- For the pinch grasp, energy expenditure and grasp stability are two contradictory principles (*Tradeoff*).

Human grasping?

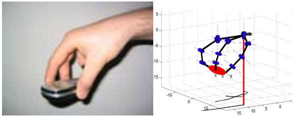
- How does the motor system control finger forces?
- What issues are raised by multi-fingered grasps?
- How does the motor system selects a particular solution among the infinite set of possible ones (Bernsteins redundant degrees of freedom problem)?
- *Trade-off between energy expenditure and grasp stability*

Multi-fingered grasps the tripod grasp

- The *increase of redundant degrees of freedom* in multi-fingered grasps raise new issues.
- It is possible to increase grasp stability without increasing energy expenditure.
- The study of this model attracted the our community from many years. Optimization Problem.

What is needed to study human grasp ?

- A biomechanical model of the hand from robotics



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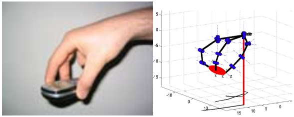
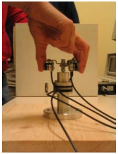


- Measuring the Human Solution



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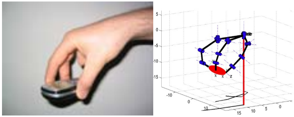

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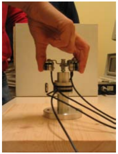
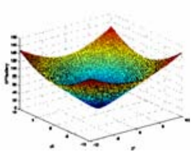
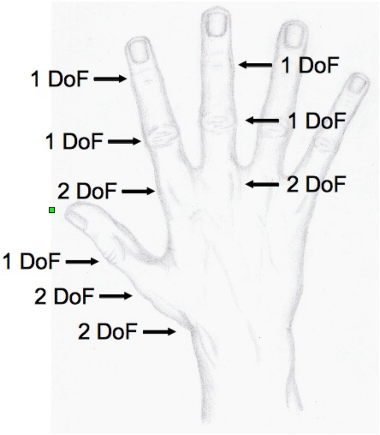


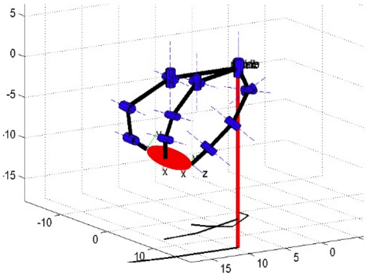
- The Internal Model able to predict (cost function)



Biomechanical/robotic model of the hand

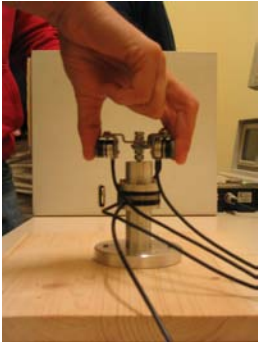


- Hand surgery
- Virtual Reality
- 13 Joints

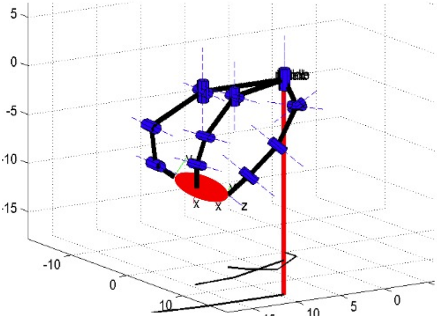


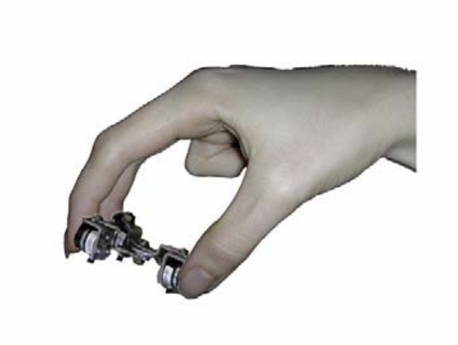
Measuring the human solution

- 6-axes FT sensor
- strain-gauges technology
- 200 Hz, 0.02 N

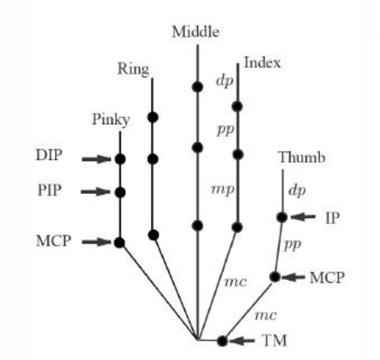


Inverse kinematics and direct measurements





Hand kinematics



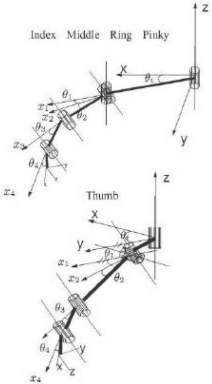
Schematic representation of the hand model, joint names:

- metacarpophalangeal (MCP),
- proximal interphalangeal (PIP),
- distal interphalangeal (DIP),
- trapeziometacarpal (TM),
- joint interphalangeal (IP):

Link names:

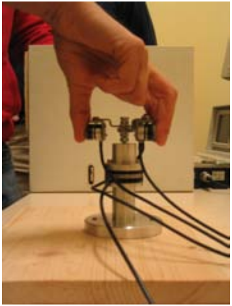
- metacarpal (MC),
- proximal phalanx (PP),
- middle phalanx (MP),
- distal phalanx (DP).

Finger kinematics

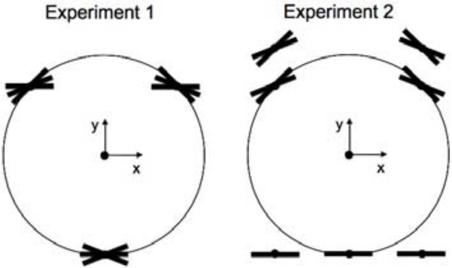


Biomech constraint $\theta_{DIP} = \frac{2}{3}\theta_{PIP}$

The experiments

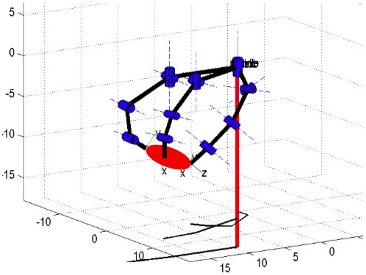


- 47 experimental conditions



Minimizing energy expenditure

- What is the direction of the finger forces that minimize torques?
- Is nature well done ?
- Does nature solve the expenditure - grasp stability tradeoff ?



- Minimize over DoFs

$$C_\tau = \tau^{\mathrm{T}} K_\tau \tau$$

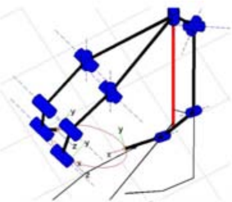
- Studies on the Human Hand based on Energy Expenditure

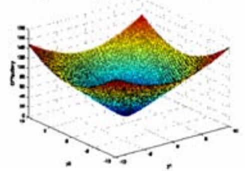
Model based on biomechanics

$$\min_{y} C(y) \qquad C = \| K\tau \|$$

$$\tau = J^{T} t$$

$$t = Ey - G^{R} f_{g}, \quad y \in \Re^{3}$$



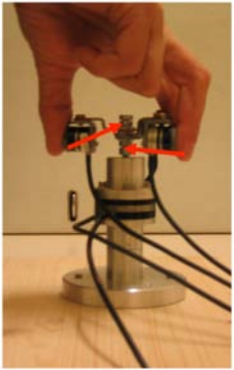


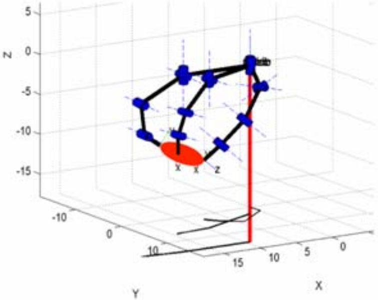
Weighting Matrices

$$K = I$$

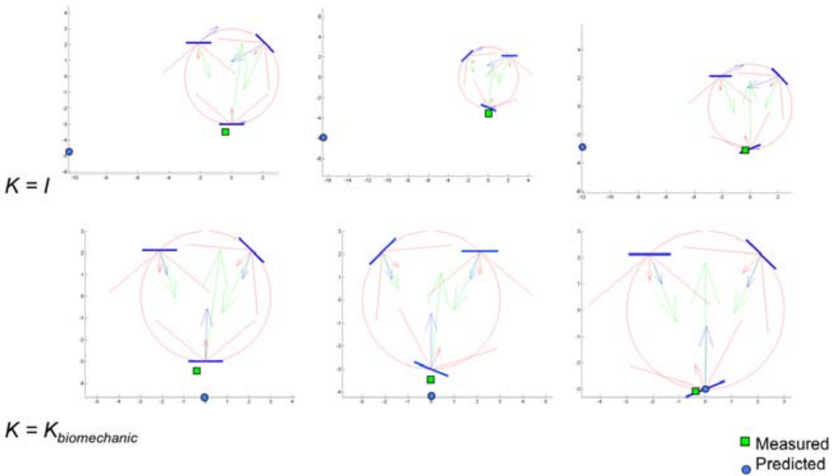
$$K = diag([\underbrace{2 \quad 1 \quad 1 \quad 1}_{\text{index}} \quad \underbrace{2 \quad 1 \quad 1 \quad 1}_{\text{medium}} \quad \underbrace{0{,}1 \quad 0{,}1 \quad 0{,}1 \quad 0{,}1}_{\text{thumb}}])$$

Measured and predicted forces

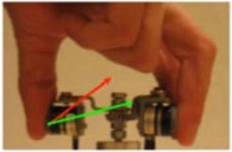


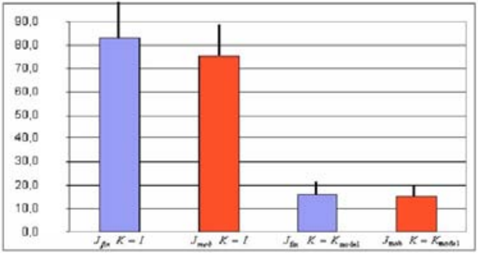


Predicted and measured force focus



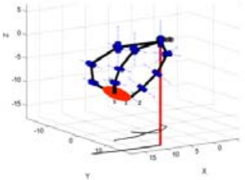
Average angular errors





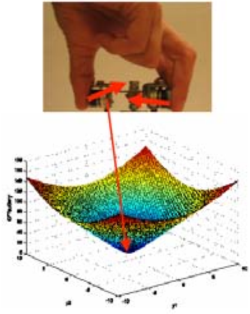
The minimum torque model

- A biomechanical model of the hand from robotics to learn what are the DoFs



- Measurements of the Human Solution

- The Energy Minimization Approach



Comments on models and prediction

- The idea is that the human hand, as the result of the evolutionary pressure, is designed in a way that it can grasp with minimum efforts.
- Best predictions has been obtained for zero external force (average).
- Development of a biomechanical model is a complex behaviour. The choice of the weighting matrix can be improved.

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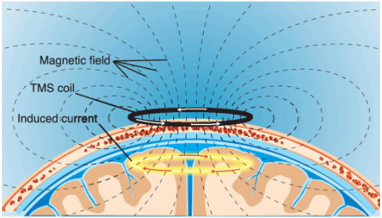
TMS Transcranial Magnetic Stimulation

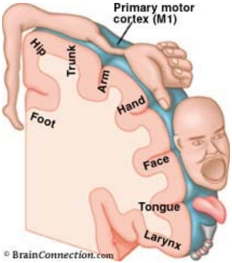
- TMS can be employed to interfere with and inihibit normal brain function (mm depth and cm radius).
- On-Off capabilities (comparison with the lesional neurophysiology)



[Ruohonen J. Background physics for magnetic stimulation. Suppl Clin Neurophysiol. 2003]

TMS and grasping

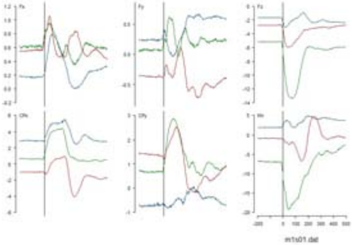
This study aimed at assessing the role of the primary motor cortex (M1) in the control of finger forces in a tripod grasp. To that end, we measured the finger forces evoked by transcranial magnetic stimulation (TMS) of the hand area of M1.

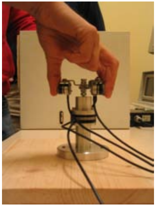


TMS & measurements

Transcranial Magnetic Stimulation TMS

Force sensor signals

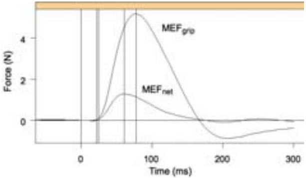




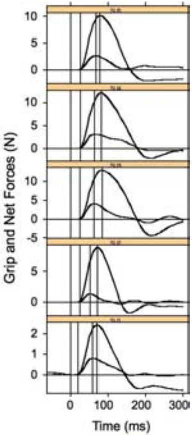
Contact forces remained approximately balanced in spite of a considerable increase in their magnitude due to TMS

This suggests that the circuits underlying this synergy, controlling the stability of the grasp are in M1

Grip and net MEFs



- MEF_{Net} force smaller than MEF_{grip}
- MEF_{grip} peaks before $MEF_{Net}(\tilde{}13ms)$



[G. Baud-Bovy, D. Prattichizzo, S. Rossi, *Brain Research Bullettin* 2008]

Pre-shaped motor action and synergies ?

The pre-shaped motor action stored at the cortical level was enhanced by TMS. This can be an evidence of synergy actuation of the human hand.

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Synergies in human hands from a robotics perspective

Synergies: experimental evidence indicates that the simultaneous motion and force of the fingers are characterized by coordination and co-variation patterns that reduce the number of independent degrees of freedom to be controlled.

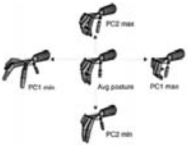
Synergies in neuroscience

Postural Hand Synergies for Tool Use

Marco Santello, Martha Flanders, and John F. Soechting
Neuroscience Department, University of Minnesota, Minneapolis, Minnesota 55455

Table 2. Percent variance accounted for by each principal component

Subjects	PC_1	PC_2	PC_3	PC_4
FC	52.9	24.7	8.4	4.8
GB	49.5	37.6	4.8	4.6
MF	74.8	13.0	5.4	2.9
MS	79.3	10.0	5.0	2.2
UH	62.9	17.2	8.6	5.9



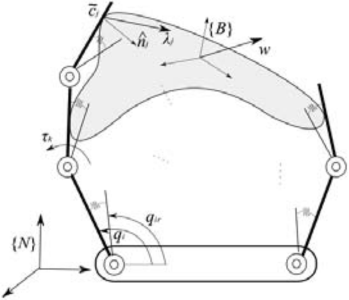
The main question

How synergies are related to internal force control ?
A model is needed: a model from a robotic perspective.

Barrett hand

Human hand

Model of the grasp



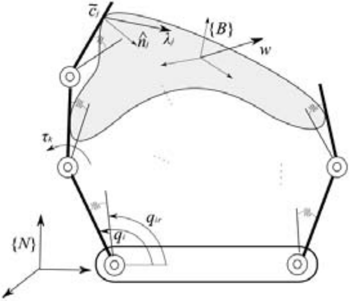
Notation	Definition
$u \in \Re^6$	position and orientation of the object
$w \in \Re^6$	external wrench applied to the grasped object
n_c	number of contact points
C_i^o	reference system at the i-th contact point on the object
$\tilde{c}_i^o \in \Re^6$	position and orientation of reference frame C_i^o
C_i^h	reference system at the i-th contact point on the hand
$\tilde{c}_i^h \in \Re^6$	position and orientation of reference frame C_i^o
λ_i	vector of forces (and moments) at the contact i
n_q	number of joints
$q \in \Re^{n_q}$	actual joint variables
$q_r \in \Re^{n_q}$	reference joint variables
τ	vector of joint forces and torques
$G \in \Re^{6 \times n_l}$	grasp matrix
$J \in \Re^{n_l \times n_q}$	hand jacobian matrix

The contact constraint:

$$\begin{bmatrix} J & -G^{\mathrm{T}} \end{bmatrix} \begin{bmatrix} \Delta q \\ \Delta u \end{bmatrix} = 0$$

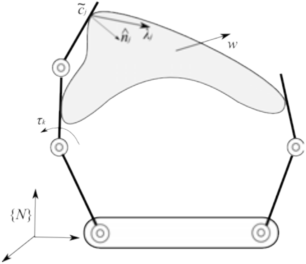
where the G is the Grasp Matrix and J the Hand Jacobian

Grasp, Jacobian, Selection Matrices



- The transpose of the complete Grasp Matrix $\tilde{G}^{\mathrm{T}} \in \Re^{6n_c \times 6}$ maps the object displacement Δu to the displacement of all the n_c contact frames $\Delta\tilde{c}^o$
$$\Delta\tilde{c}^o = \tilde{G}^{\mathrm{T}}\Delta u$$
- The complete Hand Jacobian Matrix $\tilde{J} \in \Re^{6n_c \times n_q}$ relates the joint displacement variation to the displacements of the contact frame fixed to the hand structure
$$\Delta\tilde{c}^h = \tilde{J}\Delta q$$
- The constrained velocities components are coded in the Selection Matrix $H \in \Re^{n_l \times 6n_c}$ which selects the n_l components of the relative contact velocities for all the contacts and sets them to zero:
$$H(\Delta\tilde{c}^h - \Delta\tilde{c}^o) = 0.$$
- Let $G = (H\tilde{G}^{\mathrm{T}})^{\mathrm{T}}$ be the Grasp Matrix and $J = H\tilde{J}$ be the Hand Jacobian.

Quasistatic model of the grasp



The static equilibrium of the hand and of the object is given by

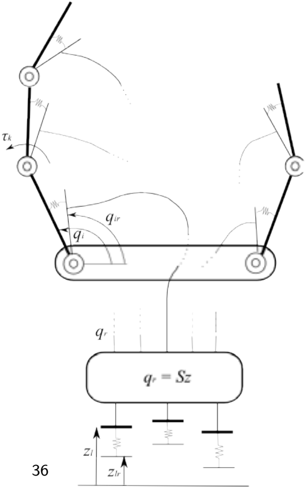
$$\begin{aligned} \tau &= J^{\mathrm{T}}\lambda, \\ w &= -G\lambda. \end{aligned}$$

General solution of eq. (1):

$$\lambda = -G^{+}w + A\xi$$

The term $A\xi$ represents the homogeneous solution, when no external load w is applied and are usually referred to as internal forces.

Hands controlled with postural synergies

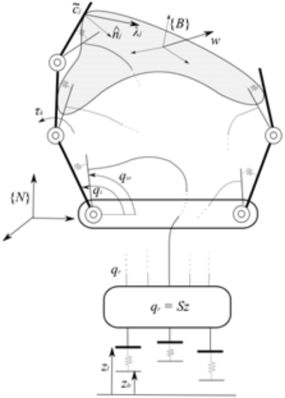


- We suppose that the hand is actuated using a number of inputs whose dimension is lower than the number of hand joint and we define it as *synergies*.
- We define the *postural synergies* as a joint displacement aggregation corresponding to a reduced dimension representation of hand movements according to a compliant model of joint torques.
- The reference vector q_r for joint variables is a linear function of *postural synergies* $z \in \Re^{n_z}$ with $n_z \leq n_q$

$$q_r = Sz$$

  through the *synergy matrix* $S \in \Re^{n_q \times n_z}$ whose columns describes the shapes, or directions, of each synergy in the joint space.

Compliant model of joint torques and synergies



A compliant model for joint torques has been chosen:

$$q_r - q = C_q \tau$$

C_q is the compliance matrix (static gains of the joint torque control and the hand link compliance), while τ are the generalized force/torque applied to the joints.

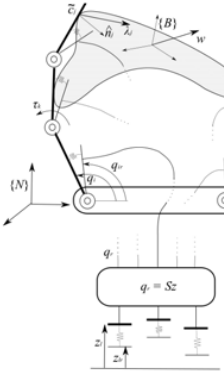
Compliant model of the synergy actuation

$$\sigma = C_z^{-1} (z_r - z)$$

σ are the synergy actuator generalized forces, C_z is a matrix whose elements are the reciprocal of the static gains of the synergy motor control.

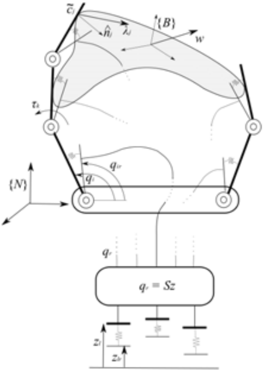
The Equilibrium Point (EP) control hypothesis [E. Bizzi, N. Accornero, W. Chapple and N. Hogan, 1984].

Controlling synergies: a quasi-static model



- consider a variation of the input synergy reference values Δz_r from the equilibrium configuration z_0.
- it leads to an actual variation of the postural synergies Δz, to a variation of the joint displacement Δq and a variation of contact forces $\Delta\lambda$ for the new equilibrium configuration of the quasi-static model and consequently to an object motion Δu

Forces and motions controlled by synergies



From Δz_r, one gets separate and not combined changes of object position Δu and contact forces $\Delta\lambda$

$$
\begin{aligned}
\Delta z &= Y\Delta z_r, \qquad \Delta q = XSY\Delta z_r \\
\Delta u &= \left(GKG^{\mathrm{T}}\right)^{-1} GKJSY\Delta z_r \\
\Delta\lambda &= (I - G_K^{+}G)KJSY\Delta z_r
\end{aligned}
$$

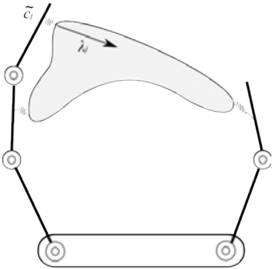
where $X = \left(I - C_q J^{\mathrm{T}}(I - G_K^{+}GKJ)\right)$,

$$K = \left(C_s + JC_qJ^{\mathrm{T}}\right)^{-1}$$

and $Y = \left(S^{\mathrm{T}}X^{\mathrm{T}}C_q^{-1}(I - X)SC_z + I\right)^{-1}$

Δu and $\Delta\lambda$ cannot be jointly, coordinately, controlled. The dimension of the controlled output $(\Delta u^{\mathrm{T}}, \Delta\lambda^{\mathrm{T}})^{\mathrm{T}}$ is larger than the dimension of controlled inputs, i.e. the number of synergies.

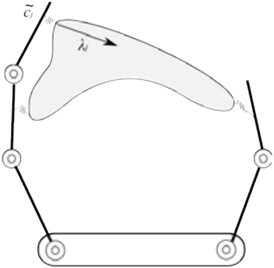
Contact compliance C_s



Contact compliance solves indeterminacy of contact forces λ in case of hyperstatic (statically indeterminate) grasp, arising when we have many contacts and a few actuated actions [Prattichizzo, Trinkle 2008].

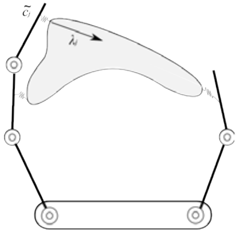
Most of the entities does not depend on C_s. For instance the subspace of controlled displacements of the object is invariant wrt structural (contact) compliance.

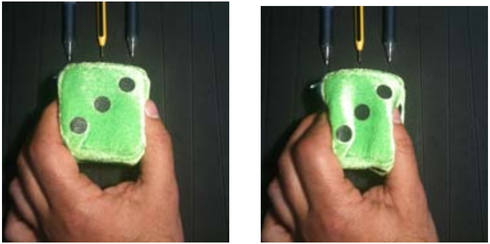
Contact compliance C_s



Contact compliance solves indeterminacy of contact forces λ in case of hyperstatic (statically indeterminate) grasp, arising when we have many contacts and a few actuated actions [Prattichizzo, Trinkle 2008].
Most of the entities does not depend on C_s. For instance the subspace of controlled displacements of the object is invariant wrt structural (contact) compliance.
Of course, contact compliance is important to model grasps of deformable objects.

Reachable internal forces $\Delta\lambda$





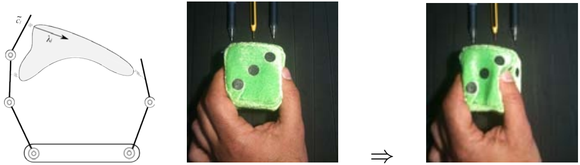
The control of internal forces is paramount in controlling the grasp. It allows to steer the contact forces to satisfy the constraints imposed by friction models at the contacts thus guarantying to not loose the contact with the object which would compromise the whole grasp.

The subspace of controllable internal forces by postural synergies:

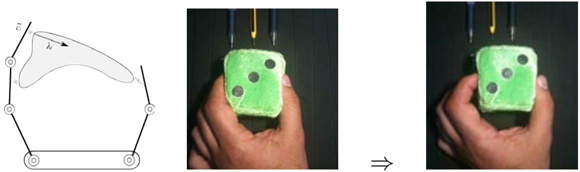
$$\mathcal{R}(E_s) = \mathcal{R}((I - G_K^{+}G)KJSY).$$

All internal forces controllable by synergy actions can be parametrized through a free vector as $E_s\alpha$.

Two types of reachable object displacements Δu



Non rigid-body motions



Rigid-body motions

Both of them are reachable controlling synergies but we are interested more in rigid-body motions which can be regarded as low energy motions, in other words they represent the natural way to change the posture of the grasped object.

Rigid-body object motions

- Rigid-body motion controllable by synergies has to be compatible with kinematic contact constraints. Thus a description of this motion can be obtained computing

$$\ker\left[JXSY \quad -G^{\mathrm{T}}\right]$$

- Under the hypothesis that the object motion is not indeterminate, i.e. $\ker(G^{\mathrm{T}}) \neq 0$, matrix Γ can be expressed as

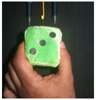
$$\Gamma = \ker\left[\begin{array}{cc} JXSY & -G^T \end{array}\right] = \left[\begin{array}{cc} \Gamma_{zr} & \Gamma_{zcs} \\ 0 & \Gamma_{ucs} \end{array}\right],$$

- Γ_{zr} is a basis matrix of the subspace of redundant motions $\ker(JXSY)$,
- Γ_{zcs} and Γ_{ucs} are conformal partitions of a complementary basis matrix.
- The image spaces of Γ_{zcs} and Γ_{ucs} consist of coordinated rigid–body motions of the mechanism, for the postural synergy references and the object position and orientation, respectively.

Internal force and object motion control

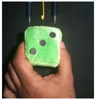
$\Rightarrow$

Internal forces ($\mathcal{R}(E_s)$)



$\Rightarrow$

Non rigid-body motions

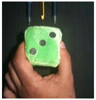


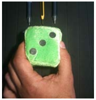
$\Rightarrow$

Rigid-body motions ($\mathcal{R}(\Gamma_{ucs})$)

Internal force and object motion control

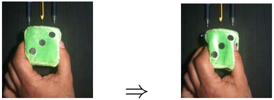
 $\Rightarrow$  Internal forces $(\mathcal{R}(E_s))$

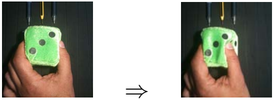
 $\Rightarrow$  Non rigid-body motions

 $\Rightarrow$  Rigid-body motions $(\mathcal{R}(\Gamma_{ucs}))$

What about controlling together (jointly and coordinately) but independently both object motions and internal forces (and redundancies) via synergies?

Internal force and object motion control

*

$\Rightarrow$ Internal forces $(\mathcal{R}(E_s))$


$\Rightarrow$ Non rigid-body motions

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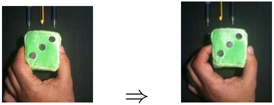
$\Rightarrow$ Rigid-body motions $(\mathcal{R}(\Gamma_{ucs}))$

What about controlling together (jointly and coordinately) but independently both object motions and internal forces (and redundancies) via synergies?

Both internal forces and rigid-body object motions.

Main result on force and motion control

- It is always possible to control, jointly but independently, the controllable internal forces, the rigid–body object motions and redundancy with the control input as synergy displacement Δz_r.

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- Algebraically, this corresponds to state that for any α, β and γ, there always exists a Δz_r solving the linear system of equations

$$\left[\begin{array}{l} E_s\alpha \\ \Gamma_{ucs}\beta \\ \Gamma_{zr}\gamma \end{array}\right] = \left[\begin{array}{r} (I - KG^T(GKG^T)^{-1}G)KJS \\ (GKG^T)^{-1}GKJS \\ I \end{array}\right]\Delta z_r$$

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- Moreover, solution for Δz_r is unique and the number of synergies n_z is equal to the sum of the dimensions of the controlled output subspaces:

$$n_z = \dim(E_s) + \dim(\Gamma_{ucs}) + \dim(\Gamma_{zr})$$

Force and motion control by synergies

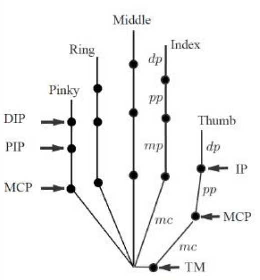
$$n_z = \dim(E_s) + \dim(\Gamma_{ucs}) + \dim(\Gamma_{zr})$$

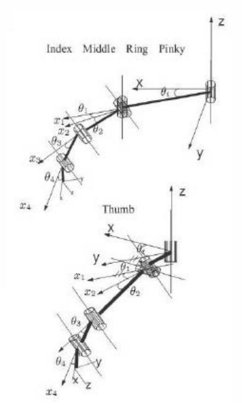
- object trajectories accomodated for by the grasp with synergies;
- contact forces controlled by synergies so as to avoid violation of contact constraints;
- reconfiguration of limbs in presence of redundancy in synergies.

Hand kinematics and dynamics

Human hand model

- 20 DoF model
- Each finger is identified by means of Denavit-Hartenberg (DH) parameters relative to each link
- Thumb joints: represent respectively thumb rotation, abduction, metacarpal and interphalangeal joints.
- For each of the other fingers, four joints have been considered, corresponding to abduction, metacarpal, proximal interphalangeal and distal interphalangeal joints.





Measuring data

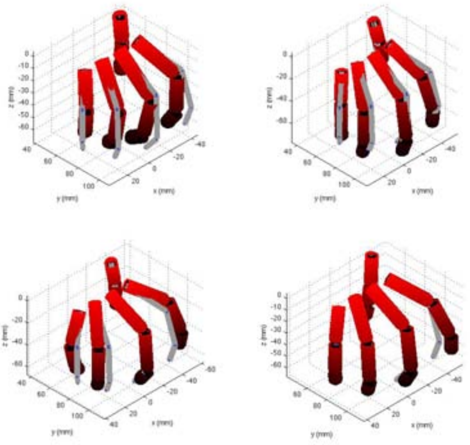
Globally 15 angles were measured by an instrumented glove, corresponding to:

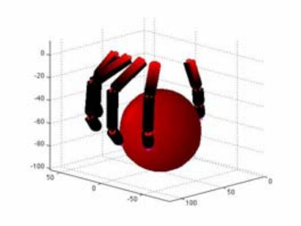
- 4 rotations for the thumb,
- 3 angles for the index,
- 2 angles for the middle,
- 3 angles for the ring, and the little;
- The middle finger abduction angle was not recorded since it is considered the reference finger in the sagittal plane of the hand.
- The Distal Interphalangeal(DI) angle is not present in none of the four fingers due to the limitation in the sensors embedded in the measuring glove.

M. Santello, M. Flanders, J. Soechting, Postural Hand Synergies for Tool Use, Neuroscience Department, University of Minnesota, Minneapolis, Minnesota 55455

Calculating synergies

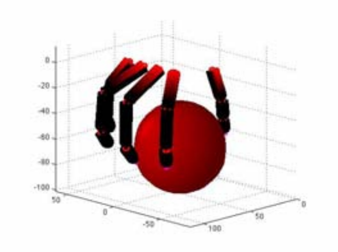
- Principal Components from the measured data
- Covariance matrix dimension is 15×15
- Data were adapted to the 20 DoF model





Tripod grasp analysis

- Contact points have been located at the tip of each finger.
- The object is grasped with the thumb, index and middle fingers, so the contact points are 3.
- Both the Hard Finger (HF) and the Soft Finger (SF) contact models have been considered in this study.



matrix	dimension	
	3 con., HF	3 con., SF
J	9×20	12×20
G	6×9	6×12

Synergy actuated hand grasping

Dimensions of the controllable internal force, redundancy and allowable movements in case of fully actuated hand and increasing the number of the selected synergies; Case 1: 3 contact points, HF model || Case 2: 3 contact points, SF model.

	Case 1			Case 2		
n. inputs	$\#(E_s)$	$\#(\Gamma_{zr})$	$\#(\Gamma_{ucs})$	$\#(E_s)$	$\#(\Gamma_{zr})$	$\#(\Gamma_{ucs})$
fully act.	3	13	4	6	10	4
1	1	0	0	1	0	0
2	2	0	0	2	0	0
3	3	0	0	3	0	0
4	3	0	1	4	0	0
5	3	0	2	5	0	0
6	3	0	3	6	0	0
7	3	0	4	6	0	1
8	3	1	4	6	0	2
9	3	2	4	6	0	3
10	3	3	4	6	1	3
11	3	4	4	6	2	3
12	3	5	4	6	3	3
13	3	6	4	6	4	3
14	3	7	4	6	5	3
15	3	8	4	6	6	3

$$n_z = \dim(E_s) + \dim(\Gamma_{ucs}) + \dim(\Gamma_{zr})$$

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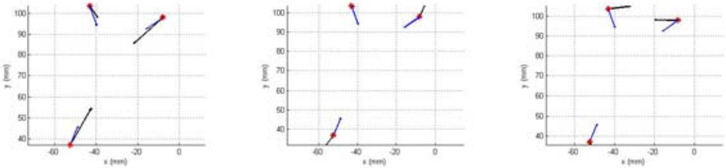
5	3	0	2	5	0	0
6	3	0	3	6	0	0
7	3	0	4	6	0	1
8	3	1	4	6	0	2
9	3	2	4	6	0	3
10	3	3	4	6	1	3
11	3	4	4	6	2	3
12	3	5	4	6	3	3
13	3	6	4	6	4	3
14	3	7	4	6	5	3
15	3	8	4	6	6	3

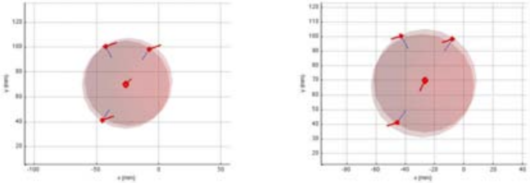
$$n_z = \dim(E_s) + \dim(\Gamma_{ucs}) + \dim(\Gamma_{zr})$$

Controllable internal forces and rigid movements

Controllable internal forces

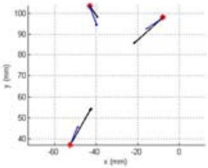


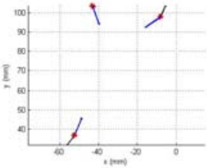
Controllable object motion

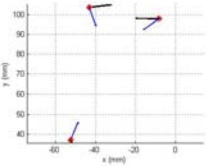


Controllable internal forces and rigid movements

Controllable internal forces







Controllable object motion

Concluding

- Grip (internal) forces control and torque minimization
- Grip forces and Transcranial Magnetic Stimulation
- Grip forces, grasp control end synergies

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Thanks for your attention!

- G. Baud-Bovy, D. Prattichizzo, N. Brogi. Does torque minimization yield a stable human grasp?. In Multi-Point Physical Interaction with Real and Virtual Objects, F. Barbagli, D. Prattichizzo, K. Salisbury (eds.), STAR, Springer Tracks in Advanced Robotics, Springer, 2005.
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