Natural encoding of user intentions in a soft prosthesis using Dynamic Synergies

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State of the art of hand prosthetics is divided between merely aesthetic or extremely simple and reliable gripper-like systems and sophisticate hi-tech poly-articular hands which are still too costly, fragile, and unintuitive to be widely used. From the data of medical records is evident that the most used upper limb prosthetic aid is constituted by cosmetic prostheses (CPs). CPs are merely aesthetic devices, designed to maximize social and self acceptance by the patient in terms of body image. Unfortunately they offer a very limited level of function. Another category of prostheses consist of body-powered prostheses (BPPs) that use an elastic grasping mechanism activated by the patient through a tendon, usually attached to a harness worn on the shoulders or some other body part. BPPs are widely used for their robustness, ease of use and low cost. Both these category of prostheses are totally passive, whereas motion is either totally absent or generated by the user. The active prostheses, instead, do no need a physical effort from the patient in order to generate motion, but use one or more motors for their activation.

In the category of active prostheses, the myo-electric prostheses (MEPs) reached a good diffusion. They have usually one motorized DOF, controlled by the patient thanks to signals fetched from the activation of two muscles on the surface of the residual limb. Unfortunately, a *cognitive* component of fatigue is now present, due to the concentration needed to operate the device. Finally, in the state of art of modern hand the poly-articular prostheses (PAPs) are very prominent. They are characterized by a large number of articulated joints controlled by 4 or 5 motors, in order to achieve a higher degree of dexterity and several different postures. Despite their high active dexterity most of these devices are often deficient in terms of functionality, durability, adequate cosmetic appearance, and affordability [1]. Furthermore, to control such a high number of motors require more than two surface EMG electrodes.

This problem is often solved by the adoption of switching strategies, which usually tend to be rather complex to use for the patient.

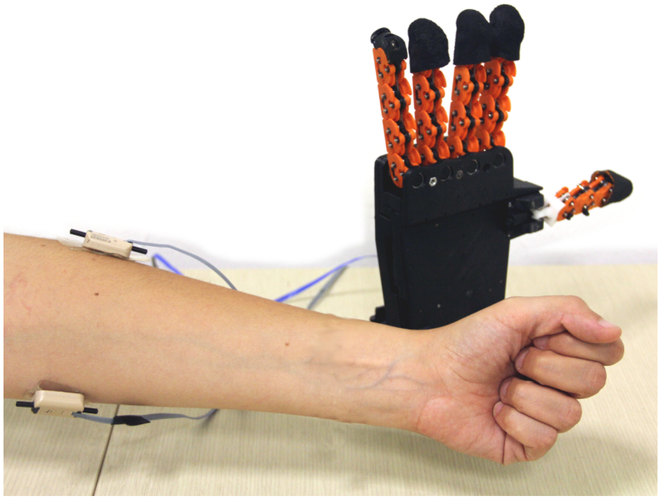

Fig. 1. The prototype of dynamic synergies prosthesis being tested. The two EMG electrodes are visible on the arm of a subject.

Another consistent amount of research revolves around increasing the performance of EMG prostheses control. Two very successful recent approaches are those based on Targeted Muscular Re-Innervation [5] and Intra-Muscular Wireless EMG transceivers [8]. Both techniques substantially increase the reading precision achieved in recording the electrical muscle activation signal and have been demonstrated able to successfully control a multi-DOF prosthesis. Unfortunately, both these approaches are invasive techniques (they require a surgery) and need a large number of electrodes.

In this work we propose an approach that tries to exploit the frequency content of EMG in an innovative and natural way. Rather than using the sort of frequency modulation that commercial EMG decoders adopt, we aim at shaping the posture of a PAP by using the velocity reference itself. This method, that we call of the *dynamic synergies*, builds on the theory of linear descriptor systems, and is based on the division of the hand movement in a slow and a fast components. In particular, different speeds are associated with different movements.

This approach comes from the observation (e.g. [6]) that precision tasks are usually performed slowly, because they require higher attention, while power task can be execute more quickly. In particular, Vainio et al. [10], [9] demonstrated that precision grip tasks on small objects require statistically longer times to be performed than power grip

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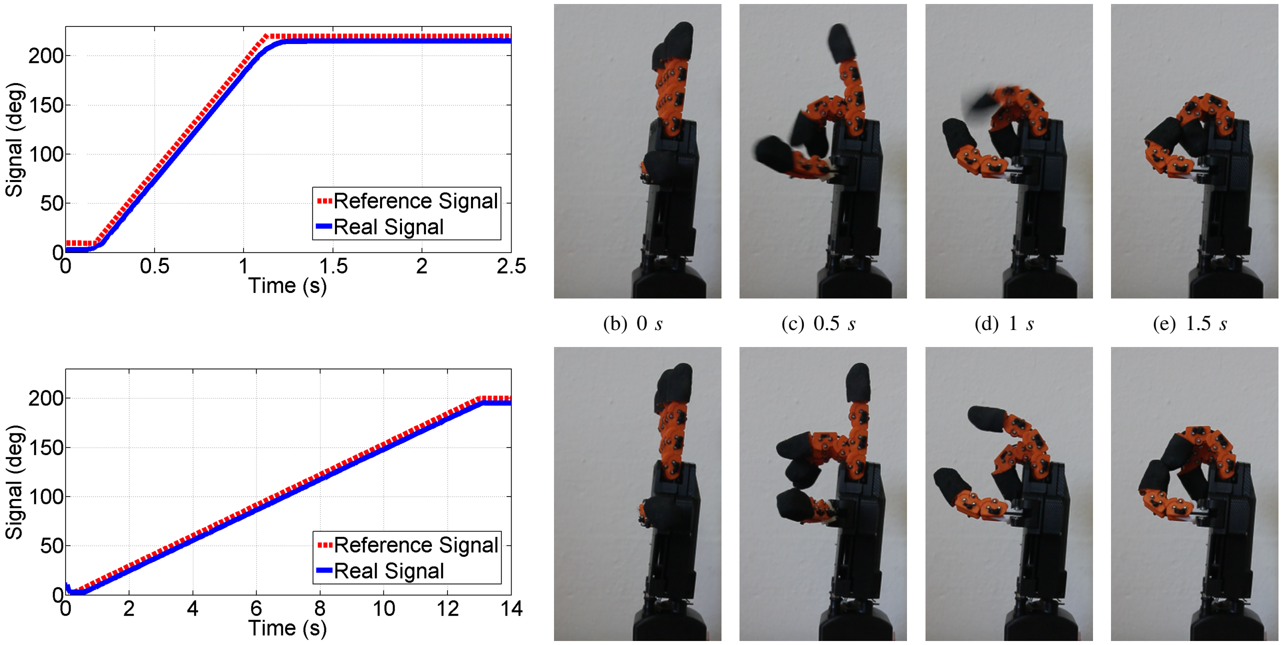
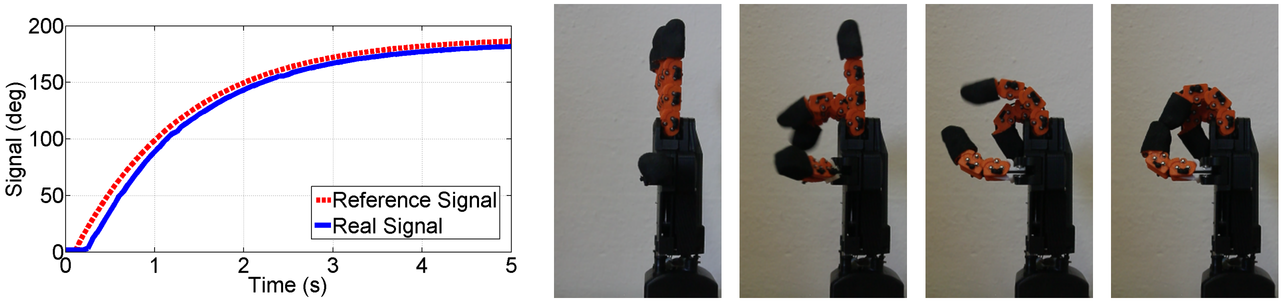


(b) 0 s (c) 0.5 s (d) 1 s (e) 1.5 s

(g) 0 s (h) 5 s (i) 10 s (j) 13 s

Fig. 2. The prototype moving along the fast synergy (top row) and along the slow synergy (bottom row), the two plots (leftmost panels) show the reference value and the effective position of the motor. The snapshots show the hand closing. It is possible to see that the fast synergy closes the hand in a fist (the primitive synergy of the power grasp) while the slow motion closes the hand in a pinch grasp. Note that the snapshots are extracted at different instants of time for the two sequences; this is in accordance with the fact that the slow synergy takes longer to close than the fast synergy. Note also that in order to maximize the decoupling, the speed of the slow synergy is very low, resulting in a rather long closure time. The closure time to obtain a pinch grasp needs not to be so slow, as it is show in Fig. 3.



(b) 0 s (c) 1 s (d) 2 s (e) 3 s

Fig. 3. Shortest time needed to obtain a pinch grasp, reference and actual motor position (a) and snapshots of the hand closing (other panels). By optimizing the reference, it is possible to seamlessly shift from the fast to the slow synergy, and thus minimize the time to closure while still obtaining a pinch grasp closure.

tasks on bigger objects. So we assume to have slower controls associated with movements that are usually slow and faster signals associated with movements that are usually fast, in order to obtain a more intuitive control. We call this idea *natural encoding of user intentions*. This idea can be implemented on PAPs with many independent motors, by the appropriate control of the different motors, or it can be *passively* embodied in the hardware of a prosthesis by using passive mechanical components as springs and dampers.

We consider here a generic adaptive hand under-actuated by means of a differential mechanism with transmission ration R. We also consider a generic linear elastic force field Eq and a set of dampers with damping factor C and transmission ratio T. Writing the equilibrium of the joint torques, we obtain the dynamic system:

$$T^T C T \dot{q} + E q = R^T u + w \,, \tag{1}$$

Where w is a generic external torque. We consider here the hand behavior for two extremal conditions: fast and slow closure. We call *slow closure* an hand closure such that $\dot{q} \simeq 0$, i.e. where the damping force effect is negligible, giving (see [3]):

$$\begin{bmatrix} -E & R^T \\ R & \emptyset \end{bmatrix} \begin{bmatrix} q \\ u \end{bmatrix} = \begin{bmatrix} w \\ \sigma \end{bmatrix} \,. \tag{2}$$

Solving it we obtain $q = R^{+}_{E^{-1}} \sigma + P^{\perp}_{R} E^{-1} w$, where $R^{+}_{E^{-1}}$ is the pseudo-inverse of R weighed on E^{-1}, and $P^{\perp}_{R} E^{-1}$ is the projector in the correspondent null-space. Hence by proper choice of E and R we can design any slow closure.

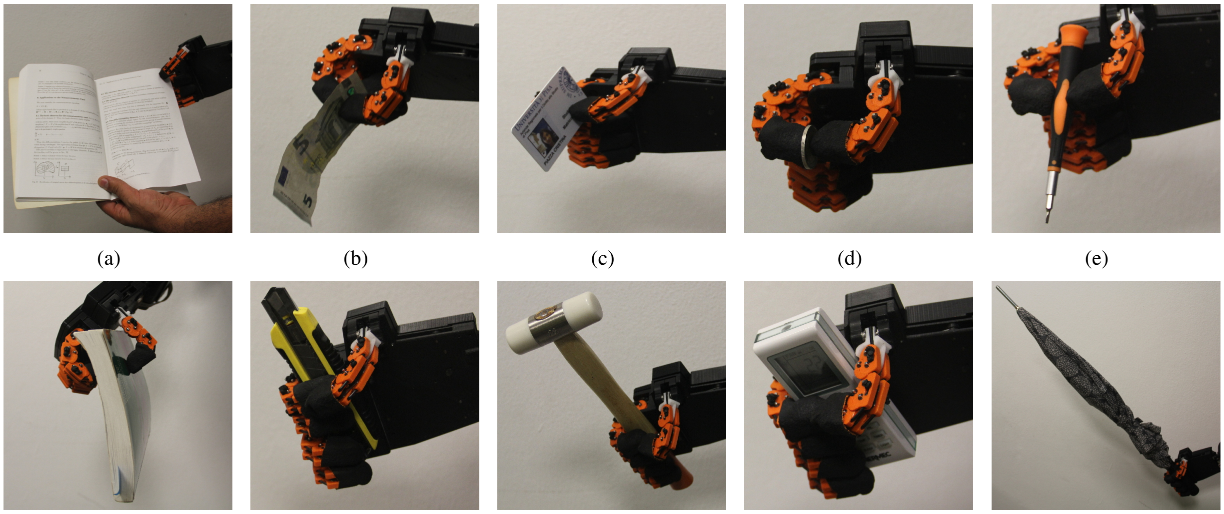

(a) (b) (c) (d) (e)
(f) (g) (h) (i) (j)

Fig. 4. Some example of grasps of different objects using SoftHand Pro-D: pinch grasps (a-e) and power grasps (f-j). In this experiment the hand was controlled using a mechanical interface.

We then call a *fast closure* the period of the hand closure in which the force u is sufficiently fast to approximate $T^T C T \dot{q} \simeq 0$ and $\dot{q} \neq 0$. In this hypothesis we obtain (see [7]):

$$\begin{bmatrix} -T_\perp E T_\perp^T & T_\perp R^T \\ R T_\perp^T & \emptyset \end{bmatrix} \begin{bmatrix} \dot{y} \\ \dot{u} \end{bmatrix} = \begin{bmatrix} \dot{w} \\ \dot{\sigma} \end{bmatrix} . \qquad (3)$$

Hence $E_y = T_\perp E T_\perp^T$ assumes the role of an equivalent stiffness matrix, and $\mathfrak{R} = R T_\perp^T$ the role of an equivalent ratio matrix. Solving w.r.t. $\dot{y}$ we obtain:

$$\dot{y} = \mathfrak{R}^+_{E_y^{-1}} \dot{\sigma} \qquad (4)$$

where $\mathfrak{R}^+_{E_y^{-1}}$ is the pseudo-inverse of $\mathfrak{R}$ weighted on E_y. Integrating, it gives:

$$y = y_0 + \mathfrak{R}^+_{E_y^{-1}} \sigma \Rightarrow q = q_0 + T_\perp^T \mathfrak{R}^+_{E_y} \sigma . \qquad (5)$$

Thus we call fast dynamic synergy matrix:

$$S_f = T_\perp^T \mathfrak{R}^+_{E_y^{-1}} , \qquad (6)$$

which identifies the obtainable hand closures when the hand is closed fast. Again the hand closure can be designed by proper choice of damping and elastic factors and pulley radii.

Relying upon these considerations, a prototype of a dynamic synergies hand was designed, called SoftHand Pro-D [7]. In particular, the SoftHand Pro-D is an evolution of the Pisa/IIT SoftHand [2] in a prototype prosthesis which, while still having 19 degrees of freedom and just one motor, can move along two different synergistic directions of motion, to perform either a pinch or a power grasp. The effectiveness of the proposed design was demonstrated in some preliminary experiments. Fig. 2 shows the hand prototype moving along the fast synergy (b-e) and along the slow synergy (g-j), controlled through a Matlab/Simulink interface. The fast ramp lead the hand toward the power grasp (the closed fist), while the slow ramp toward the pinch (thumb-index opposition). It is also possible to obtain a pinch grasp with a shift from the fast to the slow synergy during the closure movement of the hand.

This allow to minimize the time to closure to reach a pinch grasp, as is possible to see in Fig. 3.

The SoftHand Pro-D was also tested by using commercial EMGs electrodes (see Fig. 1) and, in particular, a slow muscle contraction was associated with a slow synergy while the fast synergy came from a fast muscle contraction.

Some examples of grasps of different objects are shown in Fig. 4, where the hand was controlled using a mechanical interface. Pinch grasps (a-e) and power grasps (f-j) were performed depending on the object. Future works will address proper validation of our approach with amputees patient studies.

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