Wrist Coordination in a Kinematically Redundant Stabilization Task

Lorenzo Masia, *Member*, *IEEE*, Valentina Squeri, Etienne Burdet, *Member*, *IEEE*, Giulio Sandini, and Pietro Morasso

Abstract—We investigated how the control of a compliant object is realized by the redundancy of wrist anatomy. Subjects had to balance a one degree-of-freedom inverted pendulum using elastic linkages controlled by wrist flexion/extension (FE) and forearm pronation/supination (PS). Haptic feedback of the interaction forces between the pendulum and the wrist was provided by a robotic interface. By tuning the mechanical properties of the virtual pendulum and the stiffness of the elastic linkages it was possible to study various dynamical regimes of the simulated object. Twenty subjects (divided in two groups) were tested in four days performing the same task but with different presentation order. The stabilization strategy adopted by the subjects was characterized by primarily using the PS DoF when the pendulum was linked to stiff springs and characterized by a relatively fast dynamic response; in contrast, the stabilization task was shared by both DoFs in case of lower spring stiffness and slower dynamics of the virtual object.

Index Terms—Redundant wrist control, unstable dynamics, exoskeleton wrist haptic device.

1 Introduction

A major issue in human motor control is what Bernstein [1] called the degrees of freedom problem, i.e., the apparent paradox between a small number of task variables and the usually much larger number of degrees of freedom. This large number of excess degrees-of-freedom results in motor output variability [2], [3], as the task does not fully constraints the system. In particular, given the high degree of redundancy in the upper limb, humans may use different postures of the arm and hand to solve a task [4].

How do humans choose a control strategy among the infinite many possible ones? It has been proposed that the central nervous system selects a task satisfying solution according to a cost function, in extrinsic [5] [6] or intrinsic [7], [8], [9], [10], [11] coordinates. While even online motor control can be modeled from the optimization of a cost function [12], the idea of a universal optimization criterion has recently been challenged on experimental [13], [14], and theoretical [15] reasons. Other works have analyzed highly redundant tasks with the hand from a geometrical point of view [16], [17], [18], [19], [20].

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Furthermore except for some few examples [13], [21], [22], [23], [24], [25], the vast majority of such kind of experiments on human movements were designed for free motion paradigm, thus the role of motor redundancy in the control of tasks performed in interaction with physical systems is still underinvestigated.

The problem of coordinating movements in dynamic environments may be particularly relevant to tasks requiring haptic feedback and stability during the interaction, such as in surgery [26], [27]. The main focus of the present work is to understand if different haptic responses can lead a subject to modify the redundant movement patterns.

Therefore, we designed an experiment to investigate the coordination of redundant degrees of freedom of the wrist in a task involving an unstable tool (a virtual inverted pendulum). The wrist and the tool were connected through simulated elastic linkages. The goal was to ascertain whether and how the wrist coordination strategy was dependent on the physical properties of the linkages and/or the pendulum.

Subjects had to stabilize a virtual inverse pendulum using visual and haptic feedback on the wrist, by using two degrees-of-freedom: forearm pronation/supination and wrist flexion/extension (FE), connected to the pendulum through compliant linkages. The simulated dynamics were modified by changing the parameters of the mass and height of the pendulum and the stiffness of the linkages.

The subjects could stabilize the pendulum by exploiting one or both the control channels involved in the task, i.e., wrist flexion/extension or forearm prono-supination (PS), in various combinations. The results suggest that haptic feedback of the simulated objects plays a fundamental role in the coordination between the two degrees of freedom involved in the stabilization tasks.

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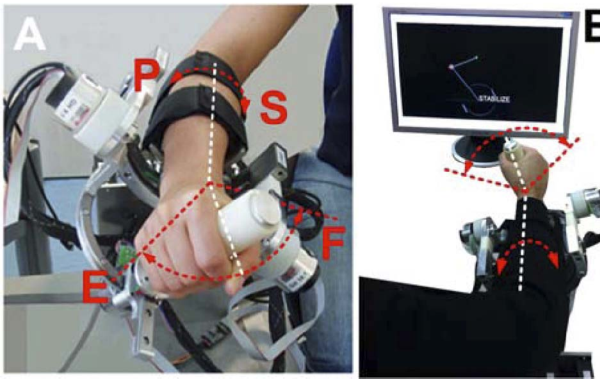

Fig. 1. A-B: experimental setup consisting of a 3D wrist haptic device and a simulated inverted pendulum in a virtual environment. Only the wrist flexion/extension and forearm pronation-supination (PS) are used, while the abduction/adduction is inactive in this experiment. White axes represent the anatomical segments of the forearm and wrist while red traces describe the movement of the two FE and PS DoFs involved in the task.

2 Methods

2.1 Experimental Apparatus and Task

The 3DOF Wrist Robot of Fig. 1, [20] developed at the Robotics Brain and Cognitive Sciences Department of the Istituto Italiano di Tecnologia (Genoa, Italy), was used in the experiments. This interface has a serial mechanical structure with the rotation axes aligned with the wrist's anatomical ones, allowing direct measurement of the wrist joint angles from the interface's encoders. Online torque feedback was provided by controlling the current flowing to the interface's motors. The task assigned to the subjects (see Fig. 2A and supplementary material, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/ToH.2012.35) was to bring up an initially tilted inverted pendulum, and balance it for a specified amount of time, by using two elastic elements: 1) a rotational spring (of stiffness K_{PS}), applied at the hinge of the simulated pendulum and controlled by forearm prono-supination; 2) a linear spring (of stiffness K_{FE}), applied to the top of the pendulum and controlled by the wrist flexion/extension. The task is redundant because there are many ways of coordinating the FE and PS DoFs for balancing the 1-DoF pendulum. The virtual pendulum was characterized by its height H and mass M. The damping coefficient D was constant making the system without excitation asymptotically stable.

The dynamic equation of the pendulum (1) shows how the pendulum (of inertia moment $I_p = MH^2$. and rotation angle θ_p) is under the action of the gravity destabilizing torque T_p (2), the damping torque T_d (3) and the two control torques T_{ps} (4) and T_{fe} (5) delivered by the two controlled DoFs PS and FE, respectively (Fig. 2B).

$$I_p\ddot{\theta}_p = -T_{ps} - T_{fe} - T_d + T_p, \tag{1}$$

$$T_p = MgH\sin(\theta_p), \tag{2}$$

$$T_d = D\frac{d\theta_p}{dt}, \tag{3}$$

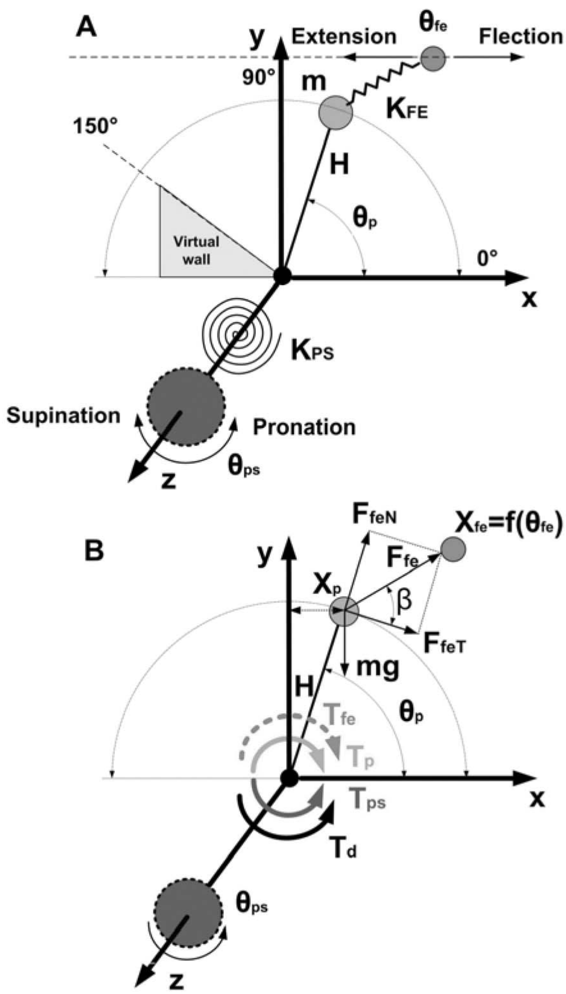

Fig. 2. Torques and force acting on the simulated pendulum. (A) The simulated pendulum and the elastic connections with FE and PS. (B) torques applied on the virtual pendulum during the stabilization task.

$$T_{ps} = K_{ps}(\theta_p - \theta_{ps}), \tag{4}$$

$$X_p = \big(H\cdot\sin\theta_p, H\cdot\cos\theta_p\big), \tag{5}$$

$$X_{fe} = f(\theta_{fe}) = G\cdot\theta_{fe}, \tag{6}$$

$$\vec{F}_{fe} = K_{fe}\,(\overline{X_{fe}X_p}), \tag{7}$$

$$F_{feT} = \left|\vec{F}_{fe}\right|\cos\beta, \tag{8}$$

$$T_{fe} = F_{feT}\,H\,. \tag{9}$$

The PS torque is simulated as a torsional spring with elastic coefficient K_{ps} and is proportional to the angular misalignment between the pendulum rotation θ_p and the PS rotation θ_{ps} measured by the wrist device (4). The FE torque is provided by a simulated spring of stiffness K_{fe}, which links the tip of the inverted pendulum X_p, whose coordinates are given by (5) and the end-effector coordinates X_{fe}, given by (6) as linear projection of θ_{fe} on the screen multiplying it by the gain G (7) that slides on a horizontal line, immediately above the pendulum (Fig. 2A), with a

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TABLE 1
Dynamic Features of the Simulated System

Dynamic (PH1)	Dynamic (PH2)	Dynamic (PH3)
$\omega_n = 22.9783 rad/s$	$\omega_n = 15.5242 rad/s$	$\omega_n = 12.5817 rad/s$
$\xi = 0.0097$	$\xi = 0.0081$	$\xi = 0.0079$
$\omega_d = 22.9772 rad/s$	$\omega_d = 15.5237 rad/s$	$\omega_d = 12.5813 rad/s$
$T = 0.2734 s$	$T = 0.4047 s$	$T = 0.4994 s$
$\upsilon = 3.6571 Hz$	$\upsilon = 2.4707 Hz$	$\upsilon = 2.0024 Hz$
$Kfe = 60 N/m$	$Kfe = 40 N/m$	$Kfe = 30 N/m$
$Kps = 120 N/m$	$Kps = 100 N/m$	$Kps = 80 N/m$
$M = 1 Kg$	$M = 1 Kg$	$M = 0.8 Kg$
$H = 0.15 m$	$H = 0.2 m$	$H = 0.25 m$
$D = 0.01 Nm/rad/s$	$D = 0.01 Nm/rad/s$	$D = 0.01 Nm/rad/s$

*Resonance frequency ω_n, damping factor ξ, damped frequency ω_d, period **T**, frequency of oscillation υ, corresponding to the gains of the simulated system: FE spring stiffness, PS spring stiffness, pendulum mass M, pendulum height H, and viscous coefficient of the pendulum D.*

motion directly controlled by the FE DoF. In particular, (8) gives the tangential component (F_{feT}) of the force vector F_{fe} exerted by the spring connected to FE which generates the torque respect to pendulum joint according (9). The dynamics of the simulated system can be modified by varying the model's parameters (K_{ps}, K_{fe}, M, H). Hence it is possible to obtain different dynamic behaviors provided to the subjects by the haptic device, and to study the effects on the coordination strategy of the FE and PS. Table 1 summarizes the three dynamics that have been investigated and Fig. 3A the corresponding behaviors.

Condition PH1 simulates a system characterized by a larger bandwidth, determined by relatively high stiffness and low height of the bar; conditions PH2 and PH3 correspond to a dynamic behavior of the pendulum with a lower bandwidth due to a longer bar and lower stiffness of the virtual springs. In these last two cases, the effect of the torque delivered by the subjects is delayed due to the compliant spring connecting the PS and FE with the simulated pendulum.

2.2 Subjects

Twenty healthy right-handed subjects (age $29 \pm 1.4y$) participated to the four days experiment in which pendula with dynamic conditions PH1, PH2, and PH3 were presented. The subjects were randomly assigned to two groups in order to examine the effect of condition sequence on their performance. Table 2 shows the different phases of the experiment from day 1 to 4. During the familiarization phase (day 1) dynamic features of the simulated pendulum were randomly presented over 35 trials; this phase allowed subjects to experience the different dynamics of pendula (by varying height, mass, and spring stiffness) and understand how the stabilization task must be executed in practice; familiarization phase will not be considered for the data analysis.

The participants were requested to balance the pendulum starting at a rest position 150 degree tilted with respect to the horizontal line (0 degree) (Fig. 3B); in the rest position the pendulum was sustained by a virtual wall so that the subject had not to deliver any torque before starting the exercise. When the message "*stabilize*" appeared on the screen, the subjects had to reach the vertical position (90 degree) in the shortest possible time and try to minimize the oscillations. Maximum allowed execution time was 15 seconds for each stabilization trial and the protocol included four phases: familiarization phase, phase1, phase2, and phase3 (one phase per day), with 35 trials per phase and a total of 140 trials. The subjects were not instructed how to use the FE and PS DoFs and free to choose a coordination strategy of the two wrist DoFs to accomplish the task. The experiment focused on analyzing the transient response of the pendulum, gathering information about the trajectories of the pendulum mass in the three different dynamic configurations and how this affects the activity of wrist FE and forearm PS.

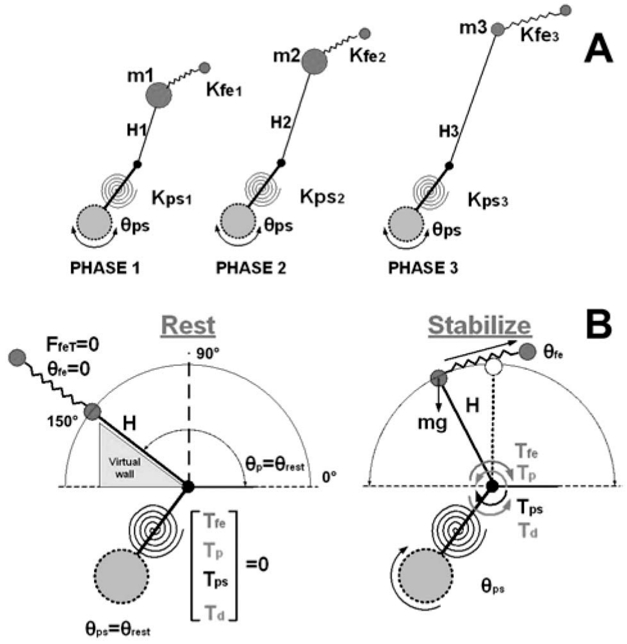

Fig. 3. A: three pendula were simulated by changing parameters as described in Table 1. B: trial execution steps: subject starts from a rest position in which a virtual wall sustains the pendulum and no torques are applied by the subjects; when the message "stabilize" appears the trial starts and the patient has 15 seconds to attempt to stabilize the pendulum vertically.

TABLE 2
Experimental Procedure

Subjects	Group	Day 1	Day 2	Day 3	Day4
Id 1	Group 1	Familiarization	Dynamic PH1	Dynamic PH2	Dynamic PH3
Id 2					
Id 3					
Id 4					
Id 5					
Id 6					
Id 7					
Id 8					
Id 9					
Id 10					
Id 11	Group 2	Familiarization	Dynamic PH3	Dynamic PH2	Dynamic PH1
Id 12					
Id 13					
Id 14					
Id 15					
Id 16					
Id 17					
Id 18					
Id 19					
Id 20					

The experiment lasted 4 days with corresponding four different phases: the familiarization phase was used to allow subjects to train using the wrist device and understanding the task.

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2.3 Analysis

Different metrics were computed to examine how participants control the inverted pendulum:

Execution time. The amount of time each subject needs to stabilize the pendulum in the vertical position and maintain it in a $\pm 10^{\circ}$ range with an angular speed lower than 10 deg/s. This time is a fraction of the 15 seconds time window corresponding to the maximum time allowed for each trial.

Damping ratio. It is a damping coefficient evaluated using the logarithmic decrement method (10), where x_1 and x_2 are two successive peaks of the pendulum oscillation around the vertical configuration. This parameter tells if subjects are able to decrease the overshoot of the pendulum when they move toward the desired position. The logarithmic decrement is used to evaluate the damping coefficient during free oscillation of a damped second-order linear system. In this experiment, the oscillations of the pendulum are not free because the input torques by the wrist device are always active. However, the damping ratio is still a useful indicator, also because the subjects tend to intermittently input impulse torques in order to balance the system around the vertical configuration. The combination of the two degrees of freedom can stabilize the pendulum in different ways depending on the two torques (FE and PS) and the shape of the oscillations around the vertical position dramatically change according the sequence of the torque impulses controlled by the device

$$\zeta = \frac{\ln x_1 / x_2}{\sqrt{(2\pi)^2 + \delta^2}}. \quad (10)$$

Power ratio. It is the ratio between the power (torque * velocity) of the FE and the one of the PS over the course of each trial (11); this metrics provides information on the activity of each degree of freedom, considering their speed profiles and their signs; if the power ratio has a value higher than 1, it means the amount of torque delivered by the FE on the virtual pendulum is predominant with respect to PS

$$\Delta P = \frac{\int_0^{T_{ex}} T_{fe}\, \dot{\vartheta}_{fe}\, dt}{\int_0^{T_{ex}} T_{ps}\, \dot{\vartheta}_{ps}\, dt}. \quad (11)$$

This last metrics provides information on the amount of coordination strategy adopted by the subjects to perform the task by using FE or PS; thus to observe what is the preferred degree of freedom chosen by the subjects during the task execution under different simulated dynamic configurations. An observation of the trend of this metrics over the course of the experiment provides information on how the voluntary control tends to be shared between the FE and PS joints.

Cross correlation. It is the measure of similarity of the two waveforms of the FE and PS torques and trajectories to find how the wrist joints involved in the task are coordinated during the dynamical interaction with the pendulum.

$$\Phi(T_{fe}, T_{ps}) = \int_{-\infty}^{+\infty} T_{fe}(t+\tau) T_{ps}(\tau) d\tau. \quad (12)$$

We assessed differences between the two groups and among the three phases using a repeated-measures ANOVA with factors GROUP (GROUP1 and GROUP2) and PHASES (PH1, PH2, PH3). When a significant difference among PHASES was detected, a Neuman-Keuls posthoc analysis was carried out to identify which couple of means was significantly different.

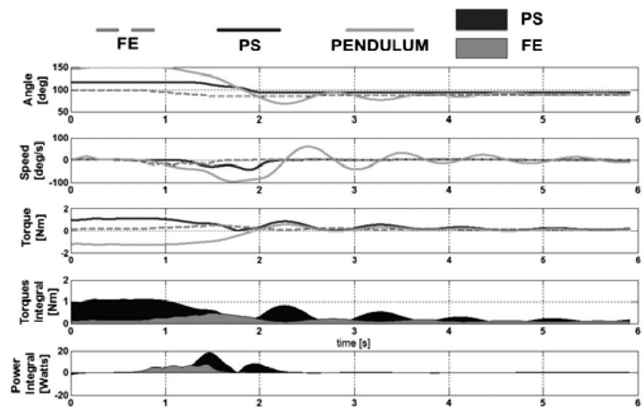

Fig. 4. Single stabilization trial. Starting from a 150 degree inclined rest position of the pendulum, the subjects were asked to stabilize it in a vertical configuration minimizing time and oscillation. Speed and torque profiles such as torque and power integral are shown in the plots below.

3 Results

All the subjects succeeded in the task in the three experimental conditions. Moreover, we found that there was a significant difference in the performance and the balancing strategy, depending on the dynamic features of the virtual pendulum. A typical task execution is depicted in Fig. 4, showing kinematic and dynamic data during a single stabilization trial. Starting from the resting position of the pendulum (150 degree with respect to the horizontal) the angle of the pendulum (solid line) reproduces the dynamic of a 1DOF second-order system when the torques are delivered by the movement of the haptic device. Force feedback is continuously provided to the subject allowing him/her to react online to the dynamics of the pendulum in order to move it upright and to maintain it in the vertical position. Torques and angular speed of the PS, FE, and pendulum joint are depicted, as well as the integral of the torques and the power. In the particular case depicted in Fig. 4, PS is the degree of freedom prevalently involved in the stabilization task.

As depicted in Fig. 5 the execution time does not significantly decrease over the course of the entire experiment, but in PH1 subjects appear to be faster in performing the required task, which might be due to the high stiffness of the springs connecting the haptic device to the pendulum. This suggests that even if the pendulum during PH1 is characterized by a faster dynamics with a higher natural frequency (Table 1) the high rigidity of the simulated elastic elements allows the subjects to manipulate it more efficiently. In contrast, in PH2-PH3, which correspond to a lower spring stiffness and lower dynamics, the amount of time needed by the subjects to stabilize the pendulum tends to increase: a significant difference was found among the three different target sets ($p < 0.05$) for both groups. Moreover, no group effect was found ($p = 0.40$), meaning that the order in which the subjects experienced the different

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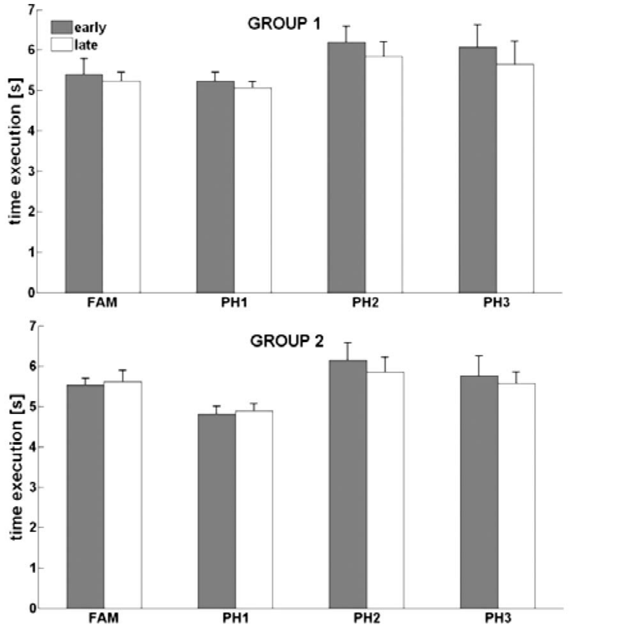

Fig. 5. Execution time is the average amount of time needed by the subjects to fulfill the stabilization criterion. Early and Late data correspond to the first and last 10 trials, respectively.

dynamic regimes was not relevant and thus data from the two groups can be analyzed together. It is also important to observe that no adaptation trend was found during each target set (35 balancing trials). The differences found in the execution time can be attributed mainly to the dynamics of the simulated pendulum.

While the execution time is not significantly different in the three experiment conditions, they affect the trajectories of the pendulum and torque signals. Traces of angular displacements, torques and power for a typical trial are depicted in Fig. 6. trajectory of the pendulum dramatically changes for the three conditions passing from an oscillating regime typical of an underdamped mechanical system to an overdamped one from phases 1 to 3, respectively.

The change in the dynamic response of the system is visible from Fig. 7A, showing the damping ratio of the pendulum-wrist system evaluated considering the final part of the oscillations (solid line from Fig. 6) around the vertical position. It is worth noticing that Table 1 indicates a decreasing damping factor ξ of the simulated pendulum from phases 1 to 3, whereas experimental data (Fig. 7A) shows an increasing damping ratio for the pendulum-wrist mechanical system passing from phases 1 to 3 with a statistically significant difference among the performance in the three tasks for both the groups ($p < 0.001$), and no difference between the groups.

A possible reason for this result comes by observing how the coordination strategy of the two DoFs of the wrist (PS and FE) changes over the course of the experiment. The power ratio (defined in the data analysis section) provides quantification on how the effort for task completion is partitioned between wrist joints: a value close to 1 indicates a similar amount of effort by the PS and FE, while a lower value indicates that the amount of effort by the PS is predominant with respect to FE.

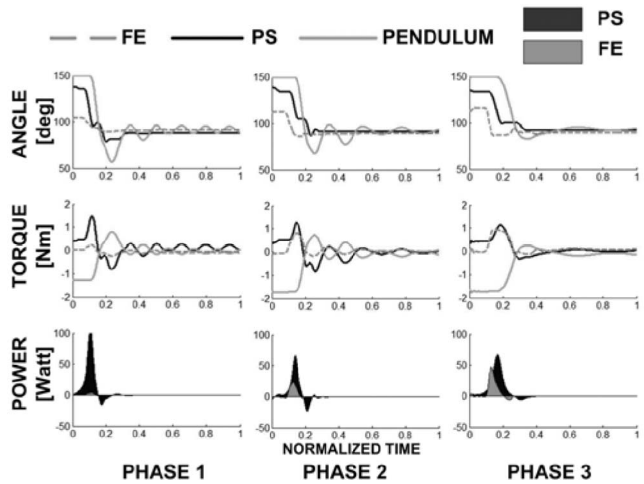

Fig. 6. Three trajectories of the pendulum during a single stabilization trial in the three dynamic conditions: angles, torques as well as power of the wrist joints are depicted, showing a clear difference in joints' movements when varying the dynamical behavior of the simulated pendulum.

Fig. 7B shows that the power ratio for all the subjects dramatically increases from PH1 to PH3 ($p < 0.001$), meaning that FE and PS powers tend to be shared between the two available degrees of freedom when the pendulum results in a configuration characterized by a lower natural dynamics. We noted that the power ratio provides information on the interaction strategy adopted by the subjects: if the overall power in a single trial has a positive value, the input torque by wrist joint is overcoming the torque by the pendulum, suggesting that the subject is positioning the pendulum actively. Contrarily, a negative power corresponds to a motion of the pendulum in an opposite direction of the ones operated by the wrist, thus we may assume that the human operator is trying to counteract the motion of the simulated object in order to restore the static equilibrium.

Fig. 8 shows the correlation among torque signals in a typical trial from each of the three phases of the experiment. The sum of the active torque due to the two DoFs is in phase opposition with respect to the destabilizing torque generated

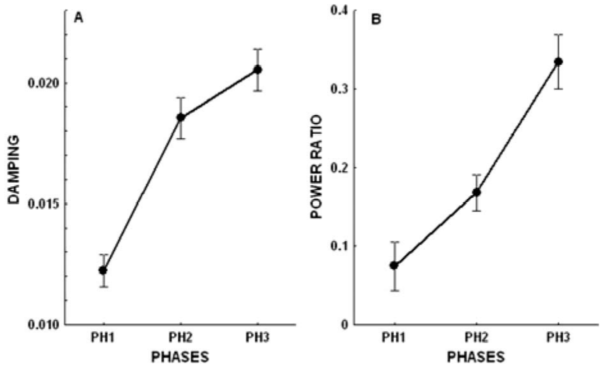

Fig. 7. (A) Damping ratio is evaluated using logarithmic decrement technique on the oscillation of the pendulum around the vertical position. During the statistical analysis of the results, all the hypotheses were tested using a 1 percent significance level. (B) Power ratio is the integral between the power of the FE divided by the power of the PS for each trial: the power ratio provides an effective measure of the real muscular activity because in its evaluation the speed of the involved joint is considered.

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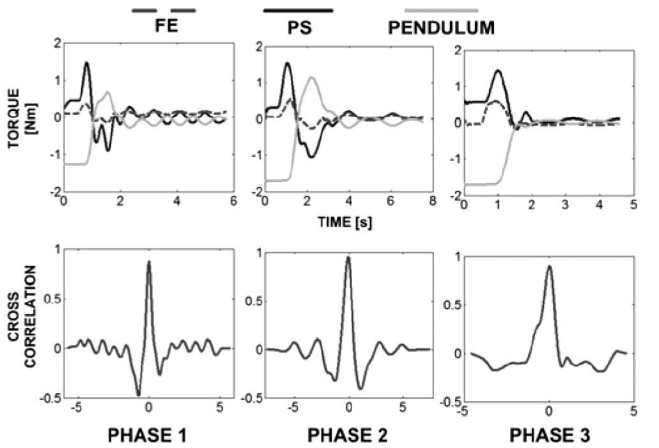

Fig. 8. The top panels show the torques of the FE and PS and the pendulum responses. The corresponding panels on the lower row shows the cross-correlation quoted at zero lag between the FE and PS torques in a given trial. Cross correlation is positive if the two signals are in phase, negative if they are in phase opposition.

by the pendulum motion, demonstrating that the subjects are capable to stabilize the pendulum. In contrast, if one considers the cross correlation between the two components of the active torques (T_{FE} and T_{PS}), they are in phase as shown from the lower panel of Fig. 8.

This finding may shed light on the strategy adopted by the subjects to stabilize the pendulum. In principle, two different strategies could be used to stabilize the pendulum: moving the two wrist DoFs together to increase the amount of torque acting on the pendulum, or trying to increase the mechanical impedance of the overall simulated system by co-contracting antagonist springs concurring on the pendulum [10]. However, increasing the voluntary contraction level of the muscles concurring to PS and FE would not contribute much to stiffen the joints because of the compliance due to the springs connecting the subject's wrist to the simulated object. However, a simple way to stabilize the oscillating mass consists of stretching the two virtual springs, thus increasing the stiffness of the overall system. This can be done by coordinating the FE and PS DoFs in order to activate the PS and FE torques in phase opposition (a positive torque by FE and a negative by PS, or vice versa). We can observe this coordination strategy by evaluating the cross correlation between FE and PS torques

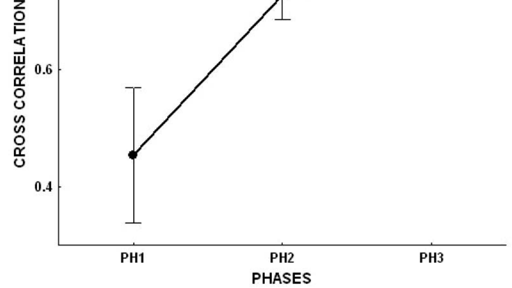

Fig. 9. Cross correlation between torques generated by FE and PS during the different phases for the two groups.

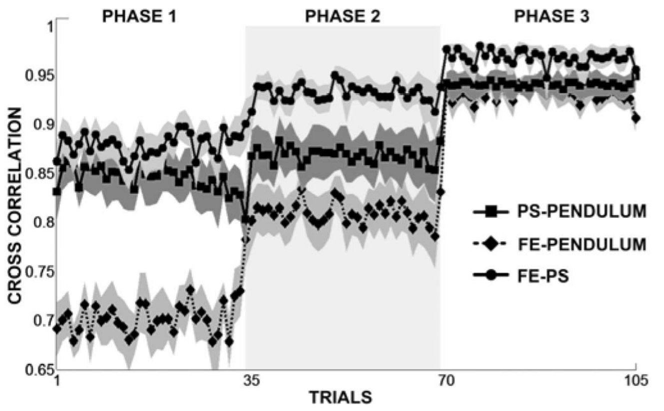

Fig. 10. Time series cross correlation between position signals of the pendulum mass, FE and PS DoFs of the subject wrist. The cross correlation among the signals results in a positively increasing trend passing from phases 1 to 3, i.e., from a fast to a slow dynamic behavior of the pendulum.

over the three experimental phases. Fig. 9 shows such finding at the population level, demonstrating that all the subjects prefer to use the two wrist DoFs to generate torques in the same direction.

In particular, Fig. 9 shows that the cross correlation has a rising trend from PH1 to PH3, resulting in a statistically significant difference among the phases ($p < 0.001$) for both groups with no difference among groups ($p > 0.758$). This is compatible with the outcomes on power ratios depicted in Fig. 7B, where the two DoFs of the wrist work in a more synergistic way to execute the task when the pendulum was characterized by a lower dynamic (PH3). This means that the subjects progressively tuned the coordination strategy between the involved DoFs, where the two virtual springs are activated in a cooperative, synergic way, adding up the stabilizing torques generated by the two DoFs.

The same cross correlation analysis of the kinematic of FE, PS, and pendulum mass is depicted in Fig. 10, showing the correlation between different position signals over the course of the three phases: the correlation among FE-pendulum, PS-pendulum, and PS-FE trajectories for all the 105 trials (without the familiarization phase) is depicted and averaged over the subjects. The figure shows not only the correlations among the various signals are prevalently positive (signals in phase) but there is a significant increase in all their values from the fast dynamic of phase 1 to the slowest one of phase 3, meaning the activations of the PS and FE tends to increase and become in phase with the pendulum movements.

Furthermore, PS and FE signals show positive correlation, suggesting that the subjects prefer producing equally oriented torques in order to stabilize the pendulum. It is worth highlighting that the FE-pendulum interaction dramatically increases in phases 2 and 3, meaning that the FE DoF becomes more active in the stabilization of the pendulum around the vertical position. This result is consistent with the previous data of damping, power ratio and cross correlation between FE and PS torques, showing also the kinematics of the DoFs involved in the manipulation of the unstable pendulum are strictly dependent on the dynamic of the object, its haptic rendering and consequently the force feedback provided and shared between the wrist joints.

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4 Discussion

The paper investigated the organization of coordination strategies developed by human subjects to stabilize an unstable load (an inverted pendulum) using a redundant, wrist-operated tool.

Previous literature mainly focused on stabilization on the lower limb with the main purpose of addressing the neural mechanism underlying human balancing while standing [28], [29], [30]. Theoretical works led to hypothesize the different strategies behind motor control and all the aspects related to sensory feedback delay [31] and reflexes [32], intermittent versus continuous control [33] and physiological factors limiting the dynamics of the manipulation [34], [35]. The approach we used for this paper is different as it focuses on a redundant effector system allowing multiple coordination patterns and multiple strategies. This corresponds to common activities of everyday life which are typically characterized by motor redundancy and strategy selection mechanisms. In particular, the proposed experimental paradigm was designed in order to study how manipulation strategies may vary under the possibility of choosing different solutions in order to perform a defined task and how the kinesthetic feedback provided by a haptic device can cause different tuning of muscular patterns.

The results showed that although redundancy is a potential factor of instability prevention, the dynamics of the environment interacting with human arm plays a fundamental role in strategies formation/tuning for the stabilization of an unstable compliant task. It is reasonable to assume that time delays in the neuromuscular and biomechanical system will limit the bandwidth of the response to external interaction, restricting the range of dynamics that is possible to balance. An accurate inspection of Figs. 4 and 6 provides important insight into the dynamic relation between the pendulum and the wrist's joints. Using stiffer springs there is a tighter mechanical coupling of wrist joints with the virtual pendulum. As stiffness decreases, the wrist movements tend to change in shape and the coordination among the DoFs involved in the task is modified.

In our experiment, the stiffness was varied in a limited range of 30-60 N/m for FE and 80-120 N/m for PS, to allow subjects succeeding in the task using only one DoF and having a good kinesthetic perception of the force feedback which represented a critical feature of the experiment design. However this still resulted in different natural frequencies in the three conditions, which led the subjects choosing a time correlated coordination of the two wrist joints, which both oscillate in phase opposition to the pendulum in order to match the balancing criteria about amplitude and speed of the residual oscillations.

The results clearly showed that the coordination strategy between the FE and PS DoFs is dependent on the sensory feedback provided by the haptic device; in fact when manipulating an object characterized by a fast dynamic response (PH1, high stiffness, and natural frequency) the subjects choose one of the two DoFs available to perform the stabilization: PS resulted to be the preferred DoF used to manipulate the pendulum during PH1, mainly because the associated spring stiffness (K_{ps}) was higher than in FE.

Furthermore, these results suggest that humans tend to prefer using the anatomical articulation which allows a faster and more rigid interaction. In contrast, when the dynamics of the interacting system are slow (PH3, low stiffness, and natural frequency) and the sensory feedback provides richer visuo-kinesthetic information, a coordination strategy between the DoFs emerges: the multiple available joints are used in order to minimize oscillation and overshooting, which may minimize the overall effort on different DoFs and prevent muscular fatigue.

Future study of how humans interact with artificial objects may help to reveal how the properties of the environment influence the coordination strategy used by the central nervous system. This may lead to more appropriate robot-assisted protocols for robotic rehabilitation, telemedicine, telemanipulation, or minimally invasive robotic surgery.

In particular, the present experiment suggests a novel approach for the rehabilitation of multijoint movements. Using the redundant inverted pendulum task for training or restoring wrist range of motion (ROM). Recovering a large ROM for each single joint requires extensive and progressive stretching protocols, which are often painful and uncomfortable for the patient. Flexion/extension movement is usually the hardest to recover, because of the length of the concurring muscles and tendons [36] which act synergistically with fingers flexion/extension. Therefore, haptic rendering may be designed in order to initially force subjects to exercise their wrist using only pronation/supination, and gradually tuning the dynamics of the pendulum to drive the task toward a progressive activation of the flexion/extension degree of freedom, as it was demonstrated in the present paper.

Another application would be using the same paradigm to train operators in performing correct actions in telemanipulation or minimally invasive surgery, training them to move specific degrees of freedom while operating by the master console [37], [38].

Although many technologically advanced instruments to improve MIS are currently available to surgeons, not many solutions have been developed that specifically improve and shorten the long and extensive training of the surgeon's hand-eye coordination and similar considerations can be formulated for all those applications where telemanipulation is required [39].

The main question will then be focused on creating artificial visuo-haptic miscalibrations by means of a haptic device and a virtual reality environment in order to train humans to remap hand movements in a modified geometrical and dynamical environment, guiding them in choosing specified joint coordination when performing actions. The primary outcomes will serve to design and develop novel mechatronic devices for the implementation of advanced Human-Computer Interfaces which will be able not only to be input channels for the interface but also to provide augmented feedback information to the user about the environment in which the manipulation is performed, providing guidance and error correction in case of failure.

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List of abbreviations

θ_p Pendulum angle
T_p Torque exerted by the pendulum motion
I_p Pendulum moment of inertia
M Pendulum Mass
H Pendulum Height
X_p Pendulum Cartesian coordinates
θ_{ps} Forearm pronation supination (PS) angle
T_{ps} Forearm pronation supination (PS) torque
θ_{fe} Wrist flection extension (FE) angle
T_{fe} Wrist flection extension (FE) torque
F_{feT} Tangential component of FE force generating torque
G Multiplication factor of θ_{fe} on the screen
ω_n Resonance frequency of the pendulum
ξ Damping factor of the pendulum
ω_d Damped frequency of the pendulum
T Oscillation Period of the pendulum
υ Frequency of oscillation of the pendulum
K_{fe} Wrist flexion extension spring stiffness
K_{ps} Forearm pronation supination spring stiffness
D Viscous coefficient of the pendulum
T_d Viscous torque at the pendulum joint
ζ Logarithmic decrement evaluated on pendulum oscillations
ΔP Power ratio between FE and PS power during task
Φ FE and PS Cross correlation

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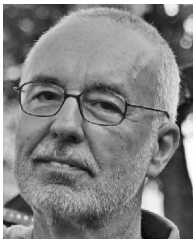

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