Inducing Human Motor Adaptation Without Explicit Error Feedback: A Motor Cost Approach

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***Abstract*—Recent studies have shown that motor adaptation is an optimisation process on both kinematic error and effort. This work aims to induce a motor adaptation in an experimental setup solely relying on the effort without any explicit kinematic error. In this experiment, the intervention space and adaptation space are decoupled: while the force field only applies to the hand linear velocity, the adaptation is expected to happen in the arm joint null space (*i.e.* the swivel angle). The primary hypothesis is that such an effort-based force field can induce a movement pattern change in an indirect manner. Secondarily, assuming that this adaptation may be further promoted through subtle prompts to explore the cost space, a variation of the approach with a progressive goal is also tested. Twenty naive subjects were allocated into two groups with slightly different implementations of the force field: one with a Constant Goal (CG) and another one with a Progressively changing Goal (PG). Subjects were asked to perform reaching tasks while attached to a 3D manipulandum. During the intervention, the device applied a resistive viscous force at the subject's hand as a function of the subject's swivel angle to encourage an increase of the latter. Significant increases of the swivel angle of 4.9° and 6.3° were observed for the CG and the PG groups respectively. This result confirms the feasibility of inducing motor adaptation in the redundant joint space by providing a task space intervention without explicit error feedback.**

***Index Terms*—Motor adaptation, motor cost, movement, reaching, robotic.**

I. Introduction

MOTOR adaptation in human motor control describes the process of changing one's movement behaviour for a given task. Such changes are commonly induced explicitly — that is, instruction (physical, verbal, or otherwise) is used to "tell" an individual how to change his/her movement. For example, in coaching sporting technique or for correcting pathological synergies after a stroke, explicit instruction is given by the coach or therapist to change the movement towards one which is preferred. In scientific literature, traditional motor adaptation experiments have also investigated adaptation with explicit error feedback. Classically subjects are asked to perform a given task, such as reaching a target, whilst their movement is perturbed by a force field [1], [2]. This perturbation results in a kinematic error between the subject's planned movement, and his/her resulting movement, which can be directly observed by the subject. The subjects are shown to adapt their motor command to accommodate for this error — a process which is primarily driven by the observation of this explicit kinematic error and the attempt to reduce it.

Recent works showed that human motor control involves the optimisation of a motor cost consisting of a combination of two components: one related to performance/error and one to energy/effort. This finding was confirmed in Emken *et al.*'s work where the human motor control was modelled as an optimisation process on a cost function with a weighted sum of kinematic error and effort [3]. Izawa *et al.*'s work also showed that with unknown stochastic perturbations, the reoptimisation process in the new environment also takes into account this uncertainty. Through practice in the new environment, the reward-based optimisation could lead human to search for a better movement pattern 1) to maximise the performance and 2) to minimise an "implicit motor cost" (here defined as the motor cost not related to the task success and/or instructions) [4].

In this work, we explore the idea of driving motor adaptation solely relying on the second component: the energy/effort. Specifically, the adaptation relies on the exploration of the cost space by the subject (through natural variability in performing the task), which is expected to instinctively drive the adaptation towards a new optimum. This adaptation is hypothesised to occur without any explicit kinematic error feedback — instead, relying only on the subjects' attempts to minimise effort in performing the task, as perceived by

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their proprioceptive feedback. Thus, the experiment has been designed in an implicit manner: with the subjects having neither instruction nor indication regarding the preferred movement.

Such an approach has been previously studied by Proietti *et al.* [5]. Their study showed that an implicit adaptation of movement redundancy using a viscous force field was possible. Their approach uses a distributed penalising force field along the limb applied by an exoskeleton to influence the subject's redundancy resolution in the arm joint null space. In this case, for a given reaching task, the force field is directly applied within the space where the adaptation occurs.

In this work, we attempt to decouple the intervention space (*i.e.* the hand task space) in which the cost is applied, from the motor adaptation space (*i.e.* the arm joint null space). With this method, the force to be exerted by the robotic system is not required to match the adaptation space, and so it has the advantages of simplicity and generality of application (*i.e.* a handle-based manipulandum device can be used to induce a motor adaptation expressed at the joint level, not physically controlled). In addition, because the adaptation space is decoupled from intervention space, the adaptation is purely driven by the subjects, and not a combination of the robotic and the subject inputs. Indeed, decoupling the adaptation space from the intervention space ensures that the subjects actually learn to produce the motor command required to achieve the task and not a complement to the force field. This indirect approach might thus be relevant in neuro-rehabilitation scenarios where re-learning of correct and efficient movement patterns plays an important role [6].

Decoupling the intervention and adaptation spaces in the perspective of neuro-rehabilitation has been previously studied by Brokaw *et al.* [7]. In their pilot study, three healthy subjects were required to move with a desired movement pattern while connected to a manipulandum robotic device which was blocking their hand movement when the movement deviated from the desired pattern. The results suggested that this method could encourage specific movement strategies. However, in this case, the required pattern is explicitly stated to subjects, limiting the conclusions that can be drawn from the study. In another study, Valdés*et al.* [8] also used indirect force feedback with a similar objective. In their study, a force field at hand as a function of trunk compensation was shown to be able to reduce the trunk compensation in stroke survivors when doing a one-dimensional reaching task. This demonstrates the feasibility and relevance of this approach, even if in that case, the force-field was coupled to explicit instructions and feedback to the subjects.

In our study, the approach, named Indirect Shaping Control (ISC), has been previously tested with five subjects [9]. Results showed that healthy subjects adapted their movements unconsciously, however, the resulting changes to the subjects' movements were not always in the expected way. In this paper, the ISC strategy is modified, both in the construction of the force field, and in the nature in which it is applied.

Besides modifying the classic ISC mentioned above, a newly designed ISC with a progressively changing goal is also introduced in this paper. Given the movement pattern change fully relies on the change of motor cost induced by an artificial force field, it may be difficult for the subjects to find the optimum with an implicit and indirect method. A progressively changing goal is usually used to improve one's capabilities gradually when the limits of those capabilities are unknown. Examples of such an approach can be seen in neuro-rehabilitation, where recovery is not achieved suddenly but rather progressively [10], [11]. Exercises and tasks are thus defined progressively to encourage motor control changes. In this process, clinicians usually set a reachable goal and move it further and further to favour changes. This applies either to practiced tasks of increasing difficulties (*e.g.* Range of Motion or finer motor control) but also to the expected changes in motor behaviours (movement quality, limitation of over-recruitment, movement smoothness or movement speed). This progressively changing goal takes its theoretical basis in physiology. Brain physiology studies and plasticity theory show that the changes in neural configuration can happen only when the inputs to the neuronal circuitry — and so the learning steps — falls within their anatomical available resources. This thus limits the learnable step size but does not ultimately prevent large-scale changes if they are presented progressively [12].

In the present study, a consistent evaluation of two variations of the ISC was thus performed where the force field encourages a change in the arm joint null space without any explicit instruction nor direct physical effect in the adaptation space. Consequently, two hypotheses were tested in this experiment. The primary hypothesis is that it is feasible to induce motor adaptation in the redundant arm joint null space by providing a task space intervention without explicit error feedback nor instruction. Furthermore, the secondary hypothesis is that utilising a progressive goal could benefit the outcome of motor adaptation in this context.

To test these hypotheses, a three-dimensional reaching task was selected. During the intervention phase, a force field, which opposed to the hand movement and only increased the movement effort, was applied at the hand. The amplitude of this viscous resistance was set as a function of the arm swivel angle (see Figure 1). The adaptation was thus expected to happen in the arm joint null space, parametrised by the swivel angle. Intervention effect was thus measured as the increase of the swivel angle during the intervention phase. Observations on potential after-effect were also performed using the same metric.

II. Methodology

A. Participants

Twenty healthy subjects (age: 23.9±3.0) participated in this experiment and were randomly allocated into the two groups (five females and five males in each group). Participants in the two groups shared the same setup and protocol with the only difference in the goal setting.

This experiment was approved by the University of Melbourne Human Research Ethics Committee (#1749444) and informed written consent was received from all subjects.

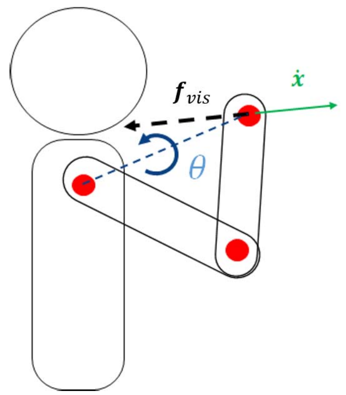

Fig. 1. The schematic of the task with the swivel angle representation (θ), hand velocity ($\dot{\mathbf{x}}$) and corresponding viscous force field ($\mathbf{f_{vis}}(\theta, \dot{\mathbf{x}})$).

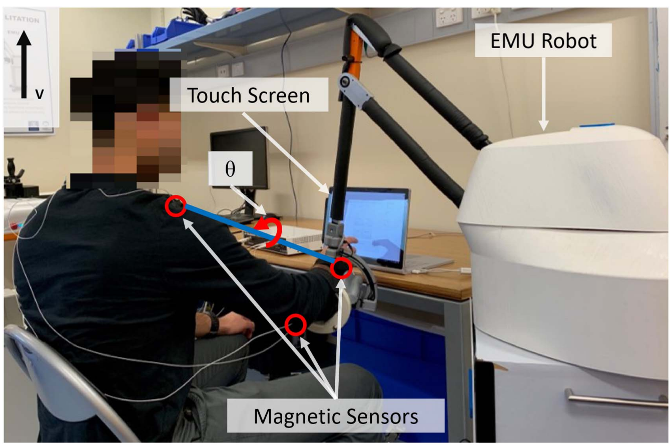

Fig. 2. The experimental setup with the EMU manipulandum, the location of the three positions magnetic sensors and the swivel angle representation (θ), where $\mathbf{v}$ is an absolute vertical unit vector.

B. Task Design

In this experiment, the objective of the robotic intervention was to increase the swivel angle (see θ in Figure 1) with which the subject was performing reaching tasks using his/her dominant hand.

Participants were required to sit on a fixed chair and repeat a reaching movement from their lap to a touch screen positioned in front of them, as shown in Figure 2. In the experiment, one of the researchers was present at all times, monitored the participants' postures, and instructed (where required) the participants to keep their backs against the back of the chair at all times. The touching target was shown on the centre of the screen and subject was asked to touch the target at their own pace. The location of the touch screen was normalised for each subject such that the height of the upper edge of the touch screen was aligned with his/her chin and that his/her metacarpophalangeal joint was touching the screen when they fully extended their arm. Within this setup, when the subject touched the button on the screen, his/her arm was not fully extended.

During the experiment, to further encourage implicit learning, a quiz game was designed to distract the subjects from the exact objective of the study. The quiz User Interface (UI) was displayed on the touchscreen with the reaching target corresponding to the quiz answers. Answer buttons were assigned randomly and setup closely to one another (within a 5 cm radius) to minimise any target position effect. No time limitation nor timing instructions were imposed to participants who were performing the reaching task at their own comfortable pace.

The swivel angle was selected for its simple representation of the arm null space in which the robotic device is incapable of direct physical effect (the EMU, displayed in Figure 2, being only able to apply 3D forces at hand) and in which configuration does not produce any kinematic error in reaching tasks. The swivel angle also accounts for a large part of the motor cost during reaching movements: the gravitational load applied to the arm (and so shoulder joints) increases while the elbow raises outside of a parasagittal plane.

C. Apparatus and Measurement

In this experiment, the EMU, a three-dimensional end-effector based rehabilitation robotic device [13], was used to generate the ISC force field. The EMU possesses three active joints, with the ability to produce linear forces in the three directions, and is terminated with a passive ball joint unit, allowing free, unconstrained rotations. The subject's hand held the handle of the device, attached to the passive unit, with their wrist strapped, preventing wrist flexion/extension and abduction/adduction. This configuration allows the device to produce a force interaction in 3D, whereas the orientation of the forearm is left free to rotate, thus producing no torque around the swivel angle axis (see [14] for a detailed kinematic analysis).

TrakSTAR 3D Guidance Magnetic Sensors (Ascension Technology Corporation, USA) was used to measure the subjects' shoulder (S), wrist (W) and elbow (E) positions, which was subsequently used to calculate the swivel angle online as follows.

Vectors $\overrightarrow{SE}$ and $\overrightarrow{SW}$ were calculated using S, E and W positions and a normal vector to the SEW plane was expressed as:

$$\mathbf{n}_{arm} = \frac{\overrightarrow{SE} \times \overrightarrow{SW}}{\left\| \overrightarrow{SE} \times \overrightarrow{SW} \right\|_2}, \tag{1}$$

where $\|\circ\|_2$ denotes the L_2 norm.

Then, assuming the subjects maintained their trunk upright, the swivel angle can be calculated as [15]:

$$\theta = \arcsin(\mathbf{n}_{arm} \cdot \mathbf{v}), \tag{2}$$

with $\mathbf{v}$ an absolute vertical unit vector.

The sensors' positions having an RMS error of 1.4mm. This results in an RMS swivel angle measurement error of 0.8° in the worst configuration.

The EMU's real-time controller (a sbRIO-9637, National Instruments Corporation, USA) was connected to a laptop which performed the force-field computation based on the swivel angle value and displayed the interface on a touch screen. All software was customised and written in LabVIEW (National Instruments Corporation, USA).

Additionally, the swivel angle as well as the sensors positions and velocities (obtained through differentiation) were recorded during the experiment for post-processing.

D. Revisit of Indirect Shaping Control (ISC)

Indirect Shaping Control was previously introduced in [9]. In [9], a viscous field was applied to the subject's hand movement as a function of the current swivel angle value. This viscous field was designed in such a way that the further the swivel angle θ is from the desired value $\theta_d(\cdot,\cdot)$, the more the force-field increased the resistance. Such a setting artificially increases the movement cost (by increasing the viscosity), the further away the movement pattern is from the desired value.

In order to take into account inter-subject natural movement variability, the desired swivel angle $\theta_d(\cdot,\cdot)$ was based on each subject's original swivel angle over the course of movement, identified during natural movements before the intervention (the PRE phase, see Section II-F). For each subject, this reference $\theta_o(d)$ was identified as a third-order polynomial of the distance to the reaching point (d) by fitting the data using a bisquare method.

For each iteration of the intervention i, an alteration goal of the swivel angle, denoted $\theta_{goal}(i)$, was defined.

In order to not influence the static posture of the subject at the initiation of movement ($d = d_0$), $\theta_{goal}(i)$ was linearly increased along the movement reaching path, starting with the subject's original posture and ending with the maximum change for the given iteration ($d = d_{max}$).

Namely, the personalised desired swivel angle $\theta_d(d,i)$ in iteration i and at a distance d from the starting point was defined as:

$$\theta_d(d,i) = \theta_o(d) + \frac{d}{d_{max}} \cdot \theta_{goal}(i) \ , \tag{3}$$

where d_{max} is the distance from the starting point to the button on the screen. For simplicity of notation, $\theta_d(\cdot) = \theta_d(\cdot, i)$ or θ_d is used when no confusion arises.

The force field thus relies on a swivel angle difference between θ_d and measurement θ. The force applied by the device at the subjects' hand is calculated as:

$$\mathbf{f}_{vis} = \begin{cases} -b_i \cdot b_k \cdot (\theta_d - \theta) \cdot \dot{\mathbf{x}}, & \text{if } \theta_d > \theta \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

where

- $\mathbf{f}_{vis}$ is the force applied at the end effector;
- $\dot{\mathbf{x}}$ is the real-time hand velocity in $m \cdot s^{-1}$;
- $\theta_d - \theta$ is the real-time difference between a desired swivel angle θ_d and the measured swivel angle θ (in degrees);
- b_i is a scalar factor changed according to the current iteration i and aims to introduce and remove the viscous field gradually during the intervention. In this experiment, b_i increases linearly from 0 to 1 in the first 15 iterations in the intervention and decreases linearly from 1 to 0 in the last 15 iterations in the intervention. b_i remains at 1 in the other iterations;
- b_k is a constant tuning gain to make the force field within a reasonable range and has been empirically set to $5000 N \cdot s \cdot (m \cdot ^\circ)^{-1}$ in the whole experiment for all subjects.

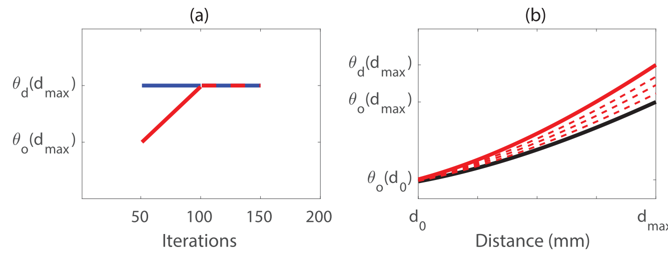

Fig. 3. (a): desired swivel angle θ_d (see Equation (3)) at the end pose ($d = d_{max}$) over iterations for C-ISC and P-ISC. (b): desired swivel angle θ_d over reaching distance for C-ISC and P-ISC with: the black solid line an example of θ_o (in PRE); the red solid line the corresponding θ_d for the second half of the INTervention applied in the PG Group and the entire INTervention phase applied in the CG Group; and the red dashed lines examples of intermediate θ_d in the first half of INTervention phase in the PG Group.

TABLE I
EXPERIMENTAL PROTOCOL

Phase	Free	PRE	INT	POST	Free
Force field	N.A.	Transparent	C-ISC / P-ISC	Transparent	N.A.
Iterations	1-25	26-50	51-150	151-175	176-200

E. Two Variations of ISC

As shown in Table I, two variations of the ISC controller were applied in the intervention depending on the group. For the group with Constant Goal (CG), similar to what proposed in [9], $\theta_{goal}(i)$ is set to a constant value of 10° across all iterations in the intervention, namely Constant-ISC (C-ISC). For the group with Progressively changing Goal (PG), Progressive-ISC (P-ISC) was used, where $\theta_{goal}(i)$ was linearly increased from 0 to 10° in the first 50 iterations and kept constant at 10° for the last 50 iterations (see Figure 3) was used.

Note that θ_{goal} was the same for both groups in the second half of the intervention and that b_i function was used in both groups for consistency and to avoid raising the subject's awareness of the removal of the force-field. A final goal of 10° increase was empirically selected after preliminary testing, to be both large enough to be observable and small enough to keep the change not noticeable by the subjects.

F. Experimental Protocol

The protocol was divided into three successive phases[1] detailed below and summarised in Table I.

1) PRE phase, where subjects performed 25 reaching tasks while strapped to the robot. In this phase, the robot was set in transparent mode, compensating only for its own weight and friction in both vertical and planar directions, to minimise its influence on the subject. The movements recorded in this phase are used to obtain a reference for each subject.
2) INTervention phase, where subjects remained strapped to the robot and performed 100 reaching tasks. The robot

[1] Two additional phases of 25 reaching tasks each without the robotic device also performed before and after these three phases and are not analysed here.

applied either the "C-ISC mode" for the CG Group or the "P-ISC mode" for the PG Group in addition to its own gravity and friction compensation.

3) POST phase, identical to the PRE phase, where subjects performed 25 reaching tasks with the robot set in transparent mode. This phase was included to measure the washout effect.

Subjects performed a total of 200 movements (including 50 movements in free conditions, see Table I). In order to reduce the potential influence of muscle fatigue, subjects were asked to take at least a thirty-second break every 20 iterations and could request additional rest at any time.

Subjects were not given any instruction about the different phases of the experiment. They were blind to the objective of the experiment and the effect of the robotic force field. Making the subjects unaware of the objective is required here to minimise to the best extent possible the influence of active or conscious behaviour on the results.

At the end of the experiments, to test their awareness of the effect of the robotic device, all subjects were asked to take a questionnaire which consisted of the following questions:

- Question 1: Did you feel the robot applying any force?
- Question 2: Do you think the robot was influencing your movement in a particular way? If yes, what was that influence?
- Question 3: Do you think you changed the way you moved during the experiment? If yes, how did you change the way you move?

G. Outcome Metrics

The viscous force and the swivel angle were calculated online using LabVIEW 2016 at a 20Hz sampling rate, and the post-processing of the data and statistical analysis were performed using MATLAB 2019b (The MathWorks Inc., USA).

1) Swivel Angle at Reach: The primary metric is the swivel angle change during the intervention and after. Only the angle at the end pose ($\theta\,(d_{max})$) was used to represent the swivel angle of the movement in the analysis.

The intervention effect is assessed through a within-group comparison of the mean swivel angles ($\theta\,(d_{max})$) of each individual in PRE phase and comparative stage of INT phase.

Similarly, the after-effect is reported by comparing the mean swivel angles ($\theta\,(d_{max})$) of each individual in PRE phase and POST phase.

Additionally, to investigate the actual change of the swivel angle induced by the intervention as well as after-effect in the POST phase, the average value $\theta_o(d_{max})$ recorded during the PRE phase for each subject was subtracted to the measures obtained in each subsequent phase. This swivel angle change was recorded as $\Delta\theta\,(d_{max})$.

For each individual, this average measure is thus reported:

- during the PRE phase, used as a baseline;
- during the comparative stage of INT phase (iterations $i = [101 - 135]$, in which both groups share the same shaping goal without the effect of b_i), to investigate the immediate effect of the ISC compared with baseline for each individual;
- during the POST phase, to investigate the after-effect of the ISC compared with baseline for each individual;

The means of $\Delta\theta\,(d_{max})$ of each individual during the comparative stage of INT phase (iterations $i = [101 - 135]$) were further compared between groups.

2) Hand Velocity: A secondary metric ϕ was introduced to evaluate the potential effect of the force field on subjects' movement "strategy". Indeed, given that the proposed additional movement cost introduced by the ISC is based on the movement velocity, a change in the velocity could explain a different optimisation from the subject to counteract this additional movement cost. The average velocities of each iteration, $\overline{\left\|\dot{\mathbf{x}}^{\{PHASE\}}\right\|}_2$, were obtained after position differentiation, and the average over the different phases was then calculated. A coefficient of velocity change between PRE and comparative stage of INT phases was then obtained for each subject as:

$$\phi = \frac{\left(\overline{\left\|\dot{\mathbf{x}}^{INT}\right\|_2} - \overline{\left\|\dot{\mathbf{x}}^{PRE}\right\|_2}\right)}{\overline{\left\|\dot{\mathbf{x}}^{PRE}\right\|_2}}, \quad \text{where} \quad \overline{\left\|\dot{\mathbf{x}}^{PRE}\right\|_2} \neq 0. \tag{5}$$

As for the swivel angle, the effect of the intervention on the hand velocity was assessed by comparing the INT and POST phases for each group, and between-group comparisons were performed to assess the effect difference of the two variations of the ISC.

H. Statistical Analysis

The normality of the data was checked using the Shapiro–Wilk test.

Within-group comparisons were tested using the Wilcoxon Signed-Rank tests, while Between-group comparisons were tested using the Wilcoxon Rank-Sum tests. As the within-group comparisons were performed on both CG and PG group, the level of significance is thus corrected to $p < 0.025$ using Bonferroni correction. The level of significance was set to 0.05 for the between-group tests.

III. Results

Results are presented in four parts, respectively presenting the subject awareness of the robotic effect, the intervention effect and the after-effect as measured by the change in swivel angle, the difference between the two groups in altering subject's movement, and the change in hand velocity.

A. Questionnaire Results

According to answers to the questionnaire, all of the subjects felt a force field was applied by the device (Q1). Only one subject (1/20) suspected that the device influenced them in a particular way but was incapable of describing the actual effect (Q2). This subject also pointed out that he felt he changed his movement to "a parabolic trajectory" during the experiment, whereas all the other subjects did not feel that they changed their movement patterns (Q3).

B. Intervention Effect Results

The changes of mean swivel angle during different phases for each individual subject in CG Group and PG Group are shown in Figure 4 and Figure 5 respectively.

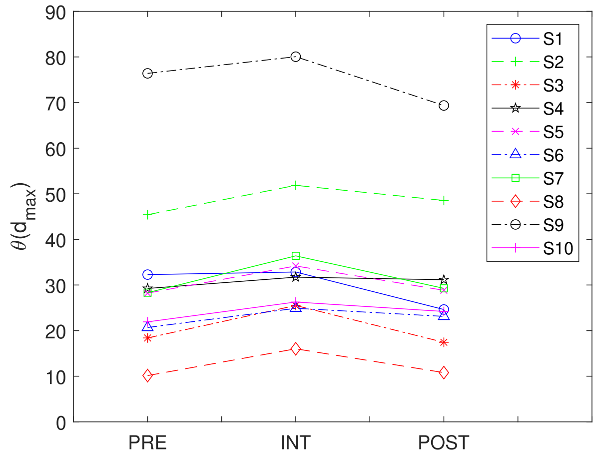

Fig. 4. Mean swivel angle measure for each individual subject in the CG Group in the 3 phases of the experiment.

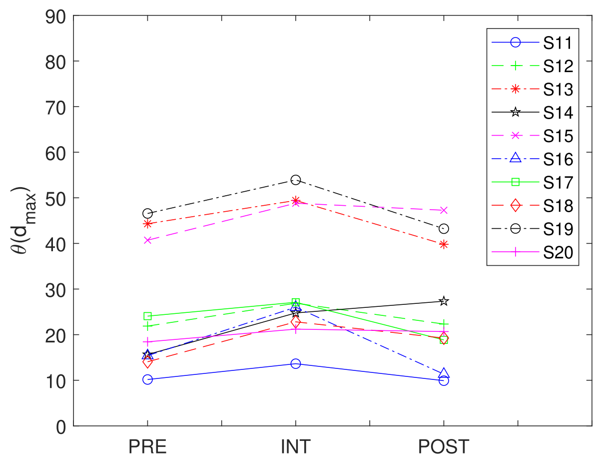

Fig. 5. Mean swivel angle measure for each individual subject in the PG Group in the 3 phases of the experiment.

TABLE II
WITHIN-GROUP COMPARISONS FOR INTERVENTION EFFECT AND AFTER-EFFECT

Group	CG (N=10)		PG (N=10)	
Phases	PRE-INT	PRE-POST	PRE-INT	PRE-POST
Difference	$+4.9°$	$-0.3°$	$+6.3°$	$+0.9°$
p value	0.002	0.6953	0.002	0.7695
Test Statistic (W)	0	23	0	24

The evolution of $\Delta\theta\,(d_{max})$ for each group is shown in Figure 6. The intervention effect is significant for both groups ($p = 0.002$), and the mean changes were 4.9° and 6.3° in the comparative stage of INT phase for CG Group and PG Group respectively, as reported in Table II. Additionally, a similar analysis performed not at the endpoint but midway through the movement (at $d = d_{max}/2$), shows a swivel angle increase of 1.9° and 2.1° for CG and PG groups respectively, suggesting that the same trend existed through the reaching movement.

As the force field was progressively removed (from iteration 135), no after-effect was observed, with a fast return to the baseline value. No significant differences are found between PRE and POST phases ($p = 0.70$ and $p = 0.77$ respectively for CG and PG Groups), with mean differences of $-0.3°$ and $0.9°$, as reported in Table II. Figures 4 and 5 show that this behaviour is relatively consistent among subjects, with only a few individuals not returning to their baseline behaviour (Subjects #9, #14, #15 and #18). Additionally, it can be seen from Figure 6 that subjects already started to return towards their baseline movement pattern during the phasing out of the force field (iterations 135 to 150).

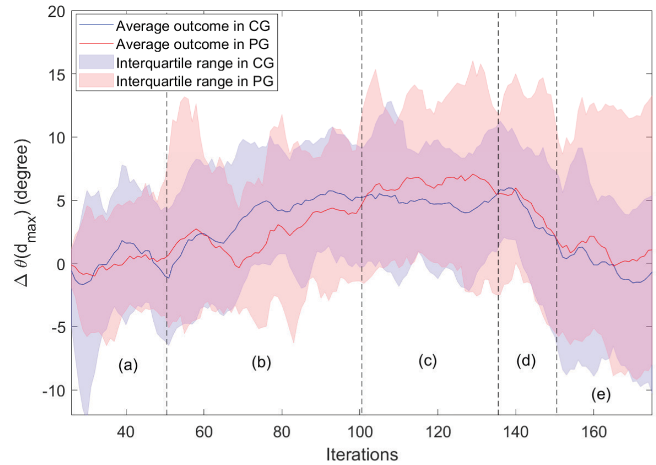

Fig. 6. Swivel angle evolution for all subjects in each group (sliding average with window width of 5 samples). The blue and red solid line show the mean outcome in each iteration for all subjects in CG Group and PG Group respectively. Shaded areas represent the interquartile range after rejecting outliers (three-sigma rule). Dotted lines show the different phases: (a): PRE, (b): first part of INT with progressive goal in PG, (c): comparative stage of INT with constant goal in both CG and PG Group, (d): progressive removal of force field, and (e): POST phase.

TABLE III
BETWEEN-GROUP COMPARISONS FOR INTERVENTION EFFECT AND AFTER-EFFECT

Phases	PRE-INT	PRE-POST
Difference	1.4°	1.2°
p value	0.2730	0.9698
Test Statistic (W)	90	104

C. Contribution of the Constant and Progressive Goal

Figure 7 shows the change of swivel angle in the two groups during the comparative stage of INT phase compared to baseline (PRE). The difference between the two groups is small, at 1.4° and found to be not statistically significant (see Table III). Similar results are observed in POST phase: the difference between the two groups is at 1.2° and found to be not statistically significant, as shown in Table III.

D. Hand Velocity

The initial reaching velocity of the subjects (in PRE phase) was $0.38 \pm 0.12 m.s^{-1}$.

The velocity change ratio ϕ (defined in Equation (5)) for each group is shown in Figure 8. A reduction of the average hand velocity of 20.1% and 15.6% was observed for the CG Group and the PG Group respectively, in both the comparative stage of INT and POST phases. The difference between the

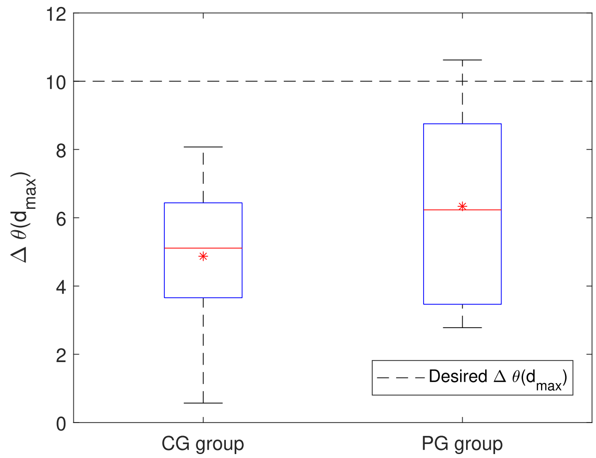

Fig. 7. Swivel angle changes compared to baseline for each group. The box plot shows swivel angle changes $\Delta\theta(d_{max})$ in the comparative stage of INT for CG Group and PG Group respectively. The bottom and top edges of the blue box indicate the 25th and 75th percentiles respectively while the red + shows the outliers. Inside the blue box, the red solid line shows the median and the red star shows the mean value of the data set.

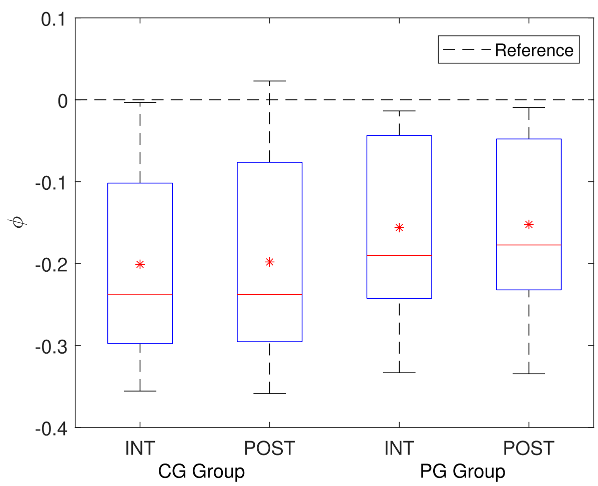

Fig. 8. Velocity change ratio for each group. The box plot shows velocity change ratio ϕ in the comparative stage of INT and POST for CG Group and PG Group respectively. The bottom and top edges of the blue box indicate the 25th and 75th percentiles respectively while the red + shows the outliers. Inside the blue box, the red solid line shows the median and the red star shows the mean value of the data set.

TABLE IV
WITHIN-GROUP COMPARISONS FOR VELOCITY CHANGES IN INT-POST

Group	CG (N=10)	PG (N=10)
Phase	INT-POST	
Difference	-0.3%	-0.4%
p value	0.695	0.922
Test Statistic (W)	23	26

two groups, 4.5%, was shown to be not significant ($p = 0.4727$) as shown in Table V. Similar results were observed for the within-group comparisons, and the difference was found to be not significant (see Table IV).

IV. DISCUSSION

A. Effects of ISC

A significant change in movement pattern was observed in both groups per their swivel angle in the comparative stage of

TABLE V
BETWEEN-GROUP COMPARISONS FOR VELOCITY CHANGE IN PRE-INT AND PRE-POST

Phases	PRE-INT	PRE-POST
Difference	4.5%	4.6%
p value	0.473	0.473
Test Statistic (W)	95	95

INT phase. Although the changes remain of relatively small amplitude (4.9° and 6.3° for the CG and PG respectively), this demonstrates the possibility that motor behaviour can be influenced in a desired "direction" (*i.e.* an increase of the reaching swivel angle) without direct physical intervention and without explicit instructions given to the subjects. The adaptation we observed in both groups is thus happening in the absence of any kinematic error, as it is purely in the arm null kinematic space and completely implicit (no subject realised the objective of the force field). This suggests that implementing a force field solely based on an artificially designed optimum can lead to an adaptation.

The adaptation of the subjects to the indirect force field falls within the reoptimisation described by Izawa *et al.* [4]: "[…] motor control in a novel environment is not a process of perturbation cancellation. Rather, the process resembles reoptimisation: through practice in the novel environment, we learn internal models that predict sensory consequences of motor commands." In this study, the novel environment is made of an indirect force-field altering the cost space, and subjects do explore this cost space and reoptimise their behaviour accordingly.

It is important to note that every subject demonstrated a change in the expected "direction" (*i.e.* an increase of the reaching swivel angle). These results strengthen the ISC approach introduced by the authors in [9] and where limited results were presented. The initial experiment and the Constant Goal (CG) group shared the same apparatus and setup but with two differences which may explain the different results. The first change is that the velocity measurement and physical contact point were at the center of the wrist in the previous work. The present work changed this to the center of the hand. Thus, the previous version potentially prevented a fully free movement around the swivel angle for the subjects due to this physical constraint at the wrist. The second change is the measurement of θ_o which is here modelled as a polynomial instead of taken as a linear relationship on constant mean value in the previous work. Thus, the previous work may have led to a more artificial linear swivel angle change along the trajectory, while the current implementation better respects the natural movement pattern reference along the path, only influencing a shift of this value.

No after-effect can be observed in either group, suggesting that the subjects quickly came back to their original movement pattern when the force field was removed. Despite the application of an implicit approach, supposedly leading to better retention [16], in this study, after-effects were not expected to happen, as the desired exaggerated new movement pattern led to a higher cost when the robotic force field was removed due to the existence of gravity. Subjects thus did not gain any benefit from this new movement pattern when they were moving without the artificial force field.

This minimal after-effect differs from the results observed by Proietti *et al.* where a direct, but implicit, movement shaping is provided with an exoskeleton [5]. In their work, a direct torque was applied to the corresponding joints to shape the joints' coordination. The retention observed in their experiment could be due to the more significant effect observed on their subjects at the end of the INTervention phase, leading to a longer washout. Additionally, in [5], the subjects' awareness was not checked after the experiment making it difficult to fully conclude whether the subjects voluntarily adapted to the force field, or were conditioned to move in a certain way when placed in the test setup.

B. Motor Cost Compromise

A side effect of the motor adaptation was also observed: the hand velocity was reduced during the intervention and maintained until the end of the experiment. This shows that even if the intervention is indirect (from task space to joint space), it has a side effect on the task space behaviour. With the ISC, the additional force introduced is in the form of a viscous force opposed to the movements in the direction of the hand's velocity, with a higher velocity causing higher viscous force magnitude. The viscous force field is proportional to both swivel angle error and velocity (as per Equation (4)), and the subjects could thus choose to comply with the swivel angle requirement, to reduce their reaching velocity, or a combination of both, in order to reduce the intensity of the force field. The force field is here inducing a cost opposed to the natural gravitational cost.

1) Cost Simulation: In order to illustrate this, a simulation of the motor cost was developed. The human arm was simplified as a two-linkage mechanism with a ball joint for the shoulder and a revolute joint for the elbow. The three main costs included in this analysis were the cost induced by the force field, the natural costs induced by gravity and kinetics. The cost (or energy consumption) is estimated as the torque-time integral (TTI), assuming that each joint has an equal contribution. Details of the simulation are provided in Supplementary A.

The costs of the reaching movements estimated for variations of the swivel angle and hand movement speed are shown in Figure 9. This simulation model does not take into account the actual muscle distribution and, as such, only gives an approximation of the cost involved. Nevertheless, the simulation result illustrates the fact that in this experiment, the cost involved by the force field was clearly acting in the opposite direction of the gravitational load and clearly dominating it. This model helps to interpret the experimental results.

2) Gravity Effect: Due to the nature of the task, the natural motor cost is dominated by the gravitational load, which is static by essence: a higher swivel angle will lead to a larger load on shoulder muscles for a given posture. A slower movement will also require additional energy, as this gravitational load will have to be sustained for a longer time, as illustrated by Figure 9-a). The force field counteracts the variations of the natural cost regarding the variation of the swivel angle as shown in Figure 9-b). The force field dominating the overall reaching cost may thus explain why subjects adapt their movement to go towards a new optimal movement cost with a higher swivel angle.

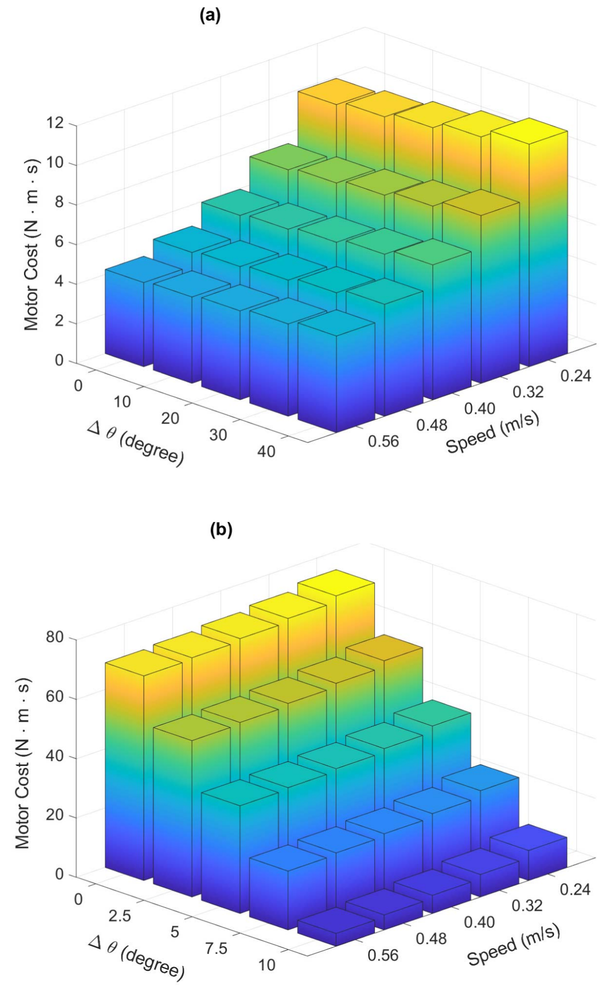

Fig. 9. Simulated motor costs without (a) and with (b) external force-field calculated as the torque-time integral for different swivel angles and hand movement speeds. Value of 0° swivel angle change and speed of $0.40 m{\cdot}s^{-1}$ corresponds to the average movement in PRE phase. An exaggerated range of swivel angle from 0° to 40° is used to make the change of natural cost due to gravity more visible.

However, it can still be seen that the average swivel angle "reached" by both groups is below the shaping goal at which the force-field component in the cost function would become zero, suggesting that subjects do not fully reach an optimal behaviour, or that some elements of the cost are not captured in this simulation.

3) Effect on Hand Movement Speed: As illustrated by Figure 9-a), the natural cost, dominated by gravity, means that a slower movement will require additional energy, as this gravitational load will have to be sustained for a longer time, but this effect of speed is clearly negligible compared to the cost of the force-field (Figure 9-b)).

Experimental results show that subjects in both groups reduced their velocity magnitude of 16% and 20% respectively for the CG and PG groups in the majority of iterations (see Figure 8). A possible explanation for this is that the subjects tried to limit the instantaneous force field effect by reducing their speed, independently of the overall movement cost. Indeed although the cost due to the force-field is itself unaffected by the movement time, the instantaneous intensity of the force is.

C. Subject Awareness

From the questionnaire results, the subject awareness can be evaluated. All participants were asked to focus on finishing the quiz and reaching tasks. As all participants could not describe the actual effect after the experiment, the training can be seen as truly implicit.

A special case among them is Subject 14 who pointed out that a change of his movement pattern occurred during the experiment, and whose shaping outcome is one of the most significant observed across the subjects (9.15°, see Figure 5). It is noted that this subject has significantly larger variations of their swivel angle than other subjects during the comparative stage of the INT phase. This variation shows a larger exploration of the cost space and potentially demonstrates that the subject noticed the force field and explicitly changed their movement pattern during the experiment. Interestingly, even though the subject was not able to describe the actual intervention effect, they still found the way to reduce the movement cost by complying with the desired movement pattern.

It is important to note that here the healthy subjects are physically capable of complying with the objective. If the subjects were explicitly described the desired movement pattern as well as the study objective, the results would be affected by how much the subjects want to cooperate with the researchers. In fact, the implicit learning approach, even if suspected to lead to better retention, may not be possible or practical in a neuro-rehabilitation context where subjects may have little movement variability of movement even to explore the cost, and thus comply with it [17]. In any case, if the shaping component of the training is left implicit, it is important, as suggested in [5] to keep another reward mechanism. This mechanism can be a task, and not shaping, related and classically in the form of gaming and/or a score to ensure motivation [18] as well as favour dopamine release to promote brain plasticity [12].

D. Contribution of the Constant and Progressive Goal

The progressive goal takes its theoretical basis in physiology. Brain physiology studies and plasticity theory show that the changes in neural configuration can only happen when the inputs to the neurons circuitry — and so the learning steps — falls within their anatomical-available resources. This thus limits the learnable step-size but does not ultimately prevent large scale changes if they are presented progressively [12]. Examples of such an approach can be seen in neuro-rehabilitation, where recovery is not achieved suddenly but rather progressively [10], [11].

In the specific case of our approach only relying on an artificial change of the motor cost, without any corresponding kinematic error, it was expected that this progressivity would assist the subject exploration of the cost space by making the minimal cost point more accessible at every step by ideally falling within the subject's natural variability.

The progressive goal approach evaluated here is shown to be slightly more effective in this context than its equivalent with a constant goal. The difference in outcome is 1.4°, which corresponds to an improvement of 29%. However, this difference is not statistically significant, and no conclusion can be drawn on the advantage of this progressivity.

The progressivity defined in this experiment was a linearly changing goal. It can be seen that the shaping outcomes varied from person to person. This suggests that adding a personalised force field could potentially contribute to enhance the contribution of this progressivity. For example, slower or pausing the movement of the goal when trainees are not able to achieve it. In clinical application, this personalisation is common, as clinicians usually offer different treatments to different patients in different stages. However, if personalised feedback is integrated into ISC, it is important to ensure that this less challenging goal does not induce slacking which may reduce human effort during rehabilitation training and cause significant reduction in the outcome of the shaping [19].

E. Translation to Neuro-Rehabilitation

The chosen task and problem in this study aims to be relevant to motor neuro-rehabilitation of the upper-limb, where pathological synergies retraining and movement correction play an important role towards functional recovery. This study aimed to provide a method in adapting human's movement pattern by adding an indirect force field. The results demonstrate the feasibility of changing the joint space coordination by using a manipulandum device by adding an artificial task space cost. Indeed, compared to the previous work using exoskeletons [5], [20], this approach allows the use of much simpler and accessible devices for the same objective. But despite cost and practicality, the indirect approach could also have the additional benefit of actually requiring the subjects to completely adopt the movement pattern by not directly physically constraining it. The effect that is observed in the redundant arm joint null space to be shaped is purely driven by the subjects, and not a combination of the robotic and the subject inputs as it is the case in studies using a direct approach applied with an exoskeleton [21].

A similar setting to ISC, using a force resistance at hand as a function of trunk compensations has also shown some positive effect in reducing compensatory movements with individuals with hemiplegia [8]. The effect was shown to be larger than classically use trunk restraint which suggests a possible translation of our proposed method to this application with the opportunity to generalise it to more complex movement pattern correction.

V. Conclusion

In this study, we investigated how an indirect force field applied to the hand in the form of an artificial motor cost could lead to a motor change within the arm joint null space. Results show that all subjects but one, either with a progressive or constant goal, did adapt their movements towards the desired movement pattern when trained using the robotic manipulandum, but no after-effect was observed in any of the two groups. These results extend the previous preliminary conclusions on such an approach and suggest that an alteration of movement patterns using an indirect motor cost approach is feasible. It would be expected that retention might be observed only at the condition that the learned movement pattern provides an actual follow-up benefit to the subjects.

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