Indirect Robotic Movement Shaping through Motor Cost Influence

Justin Fong, Vincent Crocher, Ying Tan, and Denny Oetomo

***Abstract*— Movement patterns are commonly disrupted after a neurological incident. The correction and recovery of these movement patterns is part of therapeutic practice, and should be considered in the development of robotic device control strategies. This is an area which has limited exploration in rehabilitation robotics literature. This work presents a new strategy aiming at influencing the cost associated with a movement, based on the principle of optimal motor control. This approach is unique, in that it does not directly modify the movement pattern, but instead encourages this altered movement. This 'Indirect Shaping Control' is applied in a preliminary experiment using an end-effector based device with 5 healthy subjects. The study concludes that such an approach may encourage changes in movement patterns which do persist to out-of-robot reaching actions, but this was not consistent over all subjects and further experiments are required.**

I. Introduction

Recovery from motor impairment after neurological incident can result in 'incorrect' movement patterns — stereotypically the shoulder abduction/elbow flexion synergy [1], [2]. Whilst such movement patterns often allow these individuals to produce movements —and thus allow for function— in the early stages after neurological incident, sustained use of such movement patterns can prevent recovery of normal movement patterns. This may, in turn, limit the ultimately achievable range of movements, limiting long term independence. As such, correcting these movement patterns is a common goal of rehabilitation.

Robotic devices are often seen as a potential tool in the rehabilitation process, due to their capability to provide semi-supervised or unsupervised therapy to patients at an increased dosage, with studies demonstrating their effectiveness in this space [3], [4]. However, it is important to ensure that movement patterns are correct in the exercises performed with such devices.

A second key aspect of therapy is the desire to ensure that the therapy performed generalises to other tasks or movements. Within the context of movement patterns using robotics, this can be considered ensuring movement patterns improved during a robotic therapy session are maintained when the patient is no longer in the robotic device [5].

The present work proposes an approach to both encourage specific movement patterns and generalisation of said movement patterns to movements outside of the robotic device. Although this problem has been approached using robotic exoskeletons [6] very little has been done using end-effector based devices, which have the advantages of a lower-cost and higher practicality and usability given their simpler design and easier setup.

Encouraging certain movement patterns is thus performed here using an indirect shaping approach, which creates an environment which makes certain movement patterns more physically demanding to execute, without interacting at the joint level. This approach is motivated by the theory of optimal motor control [7]–[10], which suggests that humans naturally resolve the inherent redundancy associated with movement of the human body through cost minimisation. A number of experimental and simulation studies have investigated possible factors within this cost, and it is likely that this cost has a number of components. Amongst these components, energy consumption emerges as a contributing factor.

The approach presented in this work also aims to promote generalisation of the movement pattern changes outside of the training environment by not providing explicit instruction about the force-field objective. Motor adaption studies indicate that the context or scenario in which training is performed affects how the adaptation generalises. This has been demonstrated, for example, in experiments in which different types of visual feedback are provided [11]. As such, this study also sought to explore whether providing no explicit instruction to the user (and thus having the movement pattern evolving 'naturally') would result in a generalisation of the movement pattern to movements outside the robot.

This work provides a preliminary study into this approach, proposing a dedicated robotic control strategy and an implementation on a 3D manipulandum. Investigations are then performed on 5 healthy subjects, with a simple reaching task.

II. Background

Pathological synergies after neurological incident arise as the result of cortical reorganisation after the disruption of healthy synergies due to the incident itself [12]. In this recovery process, certain 'correct' synergies may be favoured through encouragement of such movement patterns, which is reflected both in traditional therapy practices (for example, in Neurodevelopmental Techniques and Bobath Therapy [13]), as well as through the use of technology in rehabilitation.

The present work proposes an approach motivated by optimal control theory — for which some background is presented here. This is followed by a short description of existing strategies for encouraging certain movement patterns with the use of technology.

A. Optimal Motor Control

Motor activities performed by humans are commonly extremely redundant — that is, there are generally significantly

Corresponding author: fong.j@unimelb.edu.au

The authors are with the Univeristy of Melbourne - Fourier Intelligence Joint Laboratory, Melbourne School of Engineering, The University of Melbourne, Australia.

more degrees of freedom available in the human body than required to complete a task [14]. Resolution of this redundancy is often suggested to be a result of an optimisation — that, when performing a movement, humans attempt to minimise some cost function, which dictates the resulting movement patterns. The exact cost function is still a topic of investigation, and it is likely that it depends on a number of factors. However, models have been proposed on minimising a number of parameters associated with internal states, such as work [15], torque [10] and effort [9]. Furthermore, others have suggested that movements are also optimised with respect to task objectives — such as to minimise possible variance in movement at the end-effector (*i.e.* the hand) [7]. Although some debate still remains about the validity of each of these models independently, it is clear that such movements are likely to minimise a cost associated with energy consumption.

Another contributing factor to this internal optimisation is the suggestion that commonly-used movement patterns are more heavily favoured. This is manifested in 'use-dependent learning', which suggests that as particular movements are repeated, they become increasingly commonly executed with less variance [16].

Based on these principles, it is hypothesised that a modification of the environment in which an exercise is performed will result in a change in movement pattern — as the brain's natural motor control mechanisms attempt to find a new optimum. Furthermore, due to the phenomenon of 'use-based learning', repeated performance of a task with a novel movement pattern may also result in this movement pattern being preferred once the environment has been removed — *i.e.* generalisation of this movement patterns to other tasks.

B. Strategies for shaping movements using technology in rehabilitation

With the increasing number of devices being introduced for rehabilitation, and in acknowledgement that correct movement patterns are essential in rehabilitation, a number of different strategies have been proposed to encourage them.

Simpler devices alert the patients of incorrect movement patterns — such as systems providing haptic or auditory cues in case of a torso-based compensatory movement [17], [18].

In contrast, the Time-Independent Functional Training (TIFT) controller encourages correct movement patterns by only allowing task (hand) progression when correct movement patterns are performed — specifically, when the movement is made in the 'correct' joint space direction. TIFT has been implemented both with a direct feedback at the joint level [19] and with indirect feedback at the hand level [20]. Similarly, movement patterns can be efficiently constrained using exoskeleton devices as with the Kinematic Synergy Controller (KSC) [21], [22].

Another interesting approach for movement pattern correction has been to focus on individual ability for under-represented muscle groups in isometric contraction [23], which saw improvements in the pathological synergy.

It is to note that most of these approaches rely on explicit instructions about the expected change of movements patterns. As such, the specific movement pattern may be considered part of the 'task' to be achieved. Although this instruction is likely to accelerate the immediate adoption of these movement patterns, this may paradoxically reinforce their context-dependence and thus limit their generalisation. It is perhaps interesting to relate this to the well-studied Knowledge of Result (KR) and Knowledge of Performance (KP) paradigm, for which the movement pattern would generally be associated with KP [24]. It is suggested here that, in the case in which instruction is given to adhere to a given movement pattern, the movement pattern becomes KR, rather than KP — making the characteristics of the generalisation particularly hard to assess in experimental settings.

However, Proietti et al. have shown that subjects can adapt to a force-field enforcing movement patterns and generalise the learned effect to additional movements without explicit instructions [22], suggesting that this approach is viable.

The present study therefore seeks to investigate whether movement patterns can unconsciously be modified by a specific physical interaction strategy, which subtly makes it physically less demanding to follow a desired movement pattern. As a result of this unconscious adoption of the movement patterns, it is hypothesised that the movement patterns may generalise in a similar way. However, the present work does not seek to prove this specifically — this is left to a future study.

III. Methods

This first study investigates whether reaching movement patterns can be modified by changes to the dynamics of the environment, specifically at the task level (*i.e.* the hand). Based on the principle of optimal motor control, it is hypothesised that such changes will cause a change in the movement patterns. Furthermore, this study also investigates whether such changes persist in the non-modified environment.

This was investigated using a reaching task, in which healthy subjects ($n = 5$) were asked to use their dominant hand to make reaching movements towards a target. The reaching environment was modified through the use of an end-effector based robotic device, the EMU [25], with a control implementation termed 'Indirect Shaping Control'. This experiment was conducted under ethics approved by the University of Melbourne Human Research Ethics Committee, under ID 1749444.

A. Experimental Protocol

The experimental protocol was divided into three phases — Pre-Test, Intervention and Post-Test. In turn, the Pre-Test and Post-Test are divided into two conditions each — Free and Robot. (see Table I). In both the Pre-Test and Post-Test phases, no changes to the environment were used. In the Free condition, it is clear that no adjustment is possible to the environment. In the Robot condition, the robot was set to a 'transparent' mode, in which the device was set to impart

TABLE I

EXPERIMENTAL PROTOCOL

	Pre-Test		Intervention	Post-Test	
Condition	Free	Robot	Robot	Robot	Free
Control	-	Trans.	Ind. Shaping	Trans.	-
Trial No. (i)	1–25	26–50	51–150	151–175	176–200

as little force onto the subject as possible. This condition was included to investigate the possibility that simply including the robot would change movement patterns.

The Indirect Shaping Control (ISC) in the Intervention phase was introduced and phased out gradually. The magnitude of the change in environment was scaled linearly over the first 15 and last 15 trials within this phase. This was constructed to reduce the possibility that the subject would consciously change their movement pattern in response to an obvious change in environment. Furthermore, the reaching task was presented as a multiple choice quiz in order to distract the subjects from their movement patterns.

Subjects were told that they were to perform 200 movements, with the first and last 25 out of the robot. They were not told of the existence of the intervention phase. At experiment completion, the subjects were asked whether they noticed a force being applied to them by the robot, and, if so, to describe how the force was applied, if they could. This step was used to qualify whether the subjects had consciously identified the change in environment and modified their movement patterns accordingly.

B. Reaching Task

This experiment used a reaching task with the subjects' dominant hand ($n = 5$, right) whilst the subjects were seated. The reaching task required the subject to move their hand from a 'home' position next to their right knee, to a target presented on a touch screen aligned with their midline at 80% of their maximum reach distance, at approximately mid-torso height. Due to the nature of the multiple choice quiz, the position of the target on the touch screen varied slightly, but was always within the same 60×60 mm area. A new question was not shown until the hand had returned to within 30 mm of the home position. Subjects were not given specific instructions as to when they were to start or complete the movement, nor were they asked to move at a specific speed.

C. Swivel Angle

This work models the upper limb as a two link mechanism with a spherical shoulder joint, and a revolute elbow joint. Based on this model, in a reaching action, there is one redundant degree of freedom, which can be parameterised by the swivel angle. The swivel angle is defined as the angle between the plane defined by the shoulder, elbow and wrist locations, and a vertical plane including the shoulder and wrist locations [15]. With respect to Figure 1, the normal vector of the SEW plane can be calculated as:

$$\mathbf{n}_{arm} = \frac{\overrightarrow{SE} \times \overrightarrow{EW}}{\left\|\overrightarrow{SE}\right\| \left\|\overrightarrow{EW}\right\|} \quad (1)$$

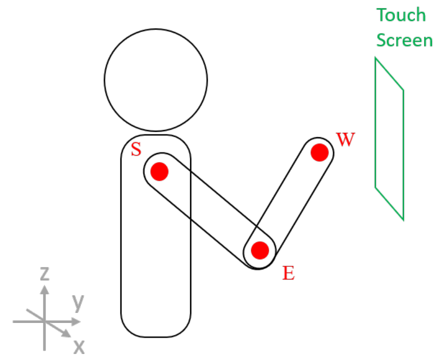

Fig. 1. Points of significance on the arm model.

Assuming the subject's torso remained straight, the swivel angle can thus be calculated as:

$$\theta = arccos(\mathbf{n}_{arm} \cdot [0, 0, 1]^T) \quad (2)$$

D. Indirect Shaping Control

The objective of the shaping strategy was to change the dynamics of the environment, to one in which a target movement pattern requires less energy to perform than the subjects' own 'normal' movement patterns. In this case, an increase in swivel angle during the movement was encouraged by application of a proportional dissipative viscous force field, $\mathbf{f}_{vis}$ at the subject hand, defined as:

$$\mathbf{f}_{vis} = -b\left(\theta, r, i\right)\dot{\mathbf{x}} \quad (3)$$

where the scalar dissipation coefficient $b\left(\theta, r, i\right)$ was constructed as a product of three parameters to encourage an increase of the swivel angle. The first parameter, $b_\theta(\theta)$ was used to explicitly make movements with lower swivel angles more difficult. The second, $b_r(r)$, scaled with distance from the original 'home' position r — to ensure that starting each movement was not too difficult, given that the swivel angle at the 'home' position was the same under all conditions. Finally, the b_i was changed according to the current trial number — such that the viscous field was gradually introduced or removed during the Intervention phase. Specifically:

$$b\left(\theta, r, i\right) = b_\theta(\theta) b_r(r) b_i \quad (4)$$

where:

$$b_\theta(\theta) = \begin{cases} 0 & \theta \geq \theta_{targ} \\ b_{max}(\theta_{targ} - \theta) & \theta < \theta_{targ} \end{cases}, \quad (5)$$

with θ defined in degrees,

$$b_r(r) = \begin{cases} \frac{r}{r_{max}} & r < r_{max} \\ 1 & r \geq r_{max} \end{cases}, \quad (6)$$

and $b_i \in [0, 1]$, dependent on the trial number.

This experiment used values of $b_{max} = 1$, $r_{max} = 250$ mm, and b_i was set to linearly ramp from 0 to 1 in the first 15 trials of the Intervention, and from 1 to 0 in the last 15 trials of the Intervention (see Figure 2).

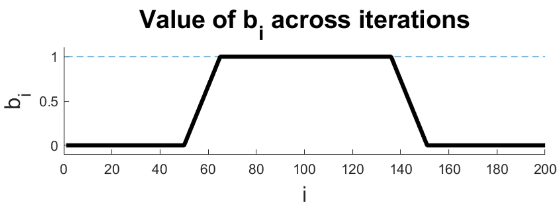

Fig. 2. Progression of b_i over the trials

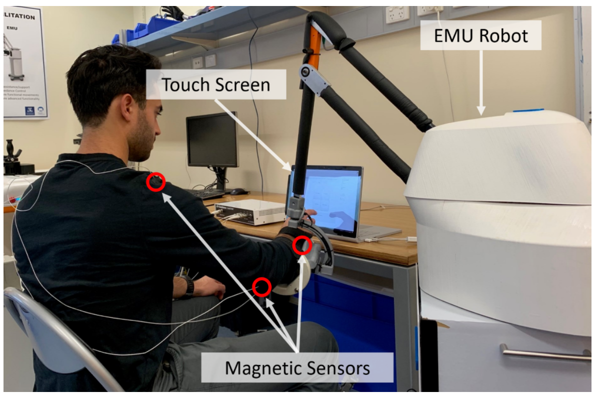

Fig. 3. The experimental setup used within this work

The choice of θ_{targ} was calculated based on the movements in the Pre-Test: Robot Phase. During this phase, the swivel angle was measured for the duration of the movement. The average swivel angle was calculated for the time during which the wrist was more than 250mm away from the starting position. θ_{targ} was then set as $15°$ more than the average of this value in all trials during the Pre-Test: Robot phase. This change in environment penalises movements with a smaller swivel angle, and makes it easier to move with a larger swivel angle (*i.e.* more shoulder abduction).

E. Equipment

The robotic device used to apply forces was the EMU device [25] — a three dimensional end-effector based device. The EMU was programmed in LabVIEW with a custom user interface, providing quiz questions, and adjusting the parameters of the EMU control strategy based on the progression through the experiment. The interface also kept track of the score, for subject motivation. Quiz questions were taken from an online open source database (Open Trivia Database, https://opentdb.com/). The experimental setup can be seen in Figure 3. The swivel angle was measured using trakSTAR 3G Guidance Magnetic Sensors (Ascension Technology Corporation, USA), with sensors positioned on the shoulder (S), elbow (E), and wrist (W). The position measurements from the system were for calculation of $\mathbf{n}_{arm}$ as per Equation (1). b was calculated according to Equation (4) at nominally 20 Hz. The data, including calculated swivel angle θ, wrist position, viscous scalar b and current movement iteration i, was also recorded continuously at 20 Hz for post-processing.

F. Data Processing and Metrics

Data was processed using Matlab 2017b. The data of interest for each movement was defined as from the time at which the hand move further than 30mm away from the home location and until the touch screen registered the touch.

1) Average Resultant Swivel Angle: In order to compare the movement patterns, each movement, i, was characterised by a single metric: the average resultant swivel angel, θ_i, which was calculated as the average angle in the second half of the movement, using a trapezoidal numeric integration to account for sampling time jitter.

2) Analysis: The experiment sought to determine whether movement patterns changed as a result of the intervention. Therefore, three comparisons were of interest, between:

- ‘Pre-Test: Robot’ and ’Intervention’: investigating whether the movement patterns changed as a result of the intervention;
- ‘Pre-Test: Robot’ and ‘Post-Test: Robot’: investigating whether the movement patterns are maintained when the environment is removed;
- ‘Pre-Test: Free’ and ‘Post-Test: Free’: investigating whether any changes in movement patterns from the robotic environment translate to free movement.

A student’s t-test was used to compare the trials in the different phases, using a Bonferroni-adjusted alpha levels of $\alpha = 0.0033 = \frac{0.05}{15}$. It is noted that for the Intervention Condition, iterations $i = 66$ to $i = 135$ were used — corresponding to the trials in which b_i was equal to 1, whereas all trials were used for all other phases.

IV. Experimental Results

Results are presented with respect to the movement patterns themselves, and the subjects’ own perceptions of the reaching environment.

A. Movement Patterns

Comparison between resultant swivel angles under the different phases reported above can be seen in Figure 4.

1) Pre-Test: Robot vs Intervention: Subjects 1, 2 and 3 all demonstrated a significant difference in their movement patterns, with resultant swivel angles changing by an average of $3.6°$, $-5.5°$ and $-4.4°$ respectively. Subjects 4 and 5 did not demonstrate a significant difference in resultant swivel angle.

2) Pre-Test: Robot vs Post-Test: Robot: Subjects 1, 2 and 3 demonstrated significant differences in their movement patterns, indicating that, as a result of the intervention, the subjects changed how they moved, by an average of $6.0°$, $-7.0°$ and $-4.9°$ respectively. The other subjects did not demonstrate a significant difference.

3) Pre-Test: Free vs Post-Test: Free: A significant difference between the Pre-Test and Post-Test Free phases was observed with Subjects 1 and 3, by an average of $3.4°$ and $-4.9°$ respectively.

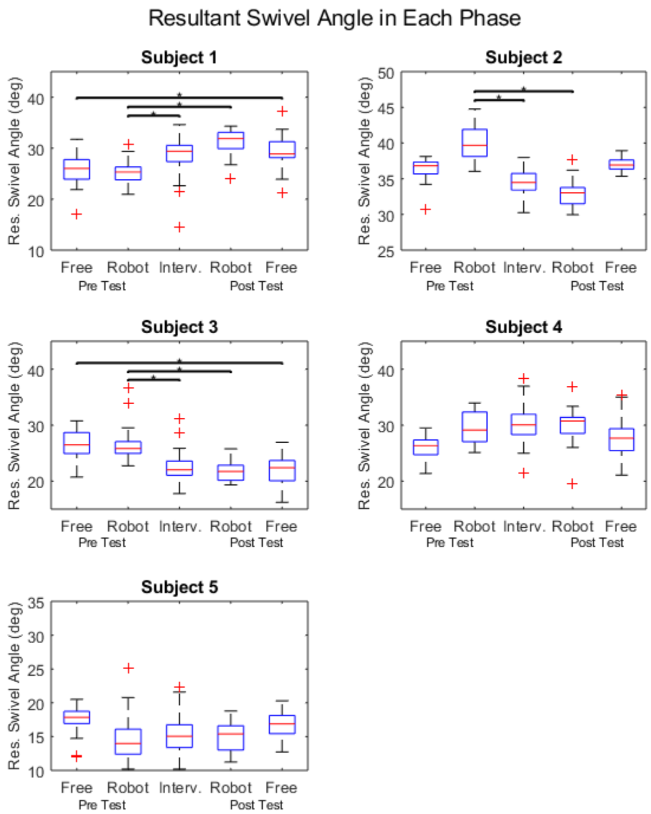

Fig. 4. Resultant Swivel Angle, for each phase, for each subject. * indicates a statistically significant difference between the two sets was observed ($\alpha < 0.0033$ i.e. Bonferroni-adjusted $p < 0.05$ for 15 trials).

B. Subjects' Perceptions

After the completion of the experiment, when asked, all subjects indicated that they had perceived a change, which made it harder for them to move. However, no subject was able to describe how the force was generated, suggesting that no subject consciously adapted their movement patterns.

V. Discussion

The preliminary results here do not present clear conclusions on the success or failure of the Indirect Shaping strategy — it is clear that the subjects responded differently to the experimental conditions. However, the results of the experiment do indicate some interesting direction for future research, and are discussed here in that context.

A. Changes in Movement Patterns

The movement patterns of Subjects 1, 2 and 3 changed as a result of the interference strategy —as evidenced by the Pre-Test: Robot and Intervention differences. Furthermore, these three subjects had significant differences between the Pre-Test and Post-Test Robot phases, in the same direction for each subject. This suggests that the interference strategy changed the movement patterns of these subjects, and that this change was not just simply a result of the dynamics of the interference strategy.

It is however, interesting to note that only Subject 1 increased their resultant swivel angle as was expected. Subjects 2 and 3 instead decreased their resultant swivel angle. This may be because the movements' biomechanical properties were not sufficiently taken into account in the construction of the ISC —that is, given the relative strength of the muscles whilst in adduction rather than abduction, the subjects may have adjusted their movement patterns to take advantage of this strength to 'fight against' the viscous field. Additionally, it is noted that a secondary 'field' exists encouraging a lower swivel angle — that of gravity, which results in a larger torque about the shoulder with a larger swivel angle. This may suggest that the overall cost for the subject may have been less when 'fighting' the force field, rather than when attempting to perform with the expected movement pattern —and thus suggest that the chosen force-field was too weak. This may be investigated in the future, by reversing the design of the force field such that a smaller swivel angle is encouraged.

Furthermore, Subjects 4 and 5 did not significantly change their movements. In these two cases, it is possible that the ISC was not strong enough to significantly change the internal cost of the reach. These results further confirm the variability in human responses, as observed in motor adaptation literature.

Despite this, it is clear that, the proposed strategy did change the movement patterns for at least some subjects. As no subject indicated knowledge of how the field was constructed, it is also suggested that these changes were a 'natural' evolution in response to the change in environment. This is a significant result, as these subjects have changed how they resolve the redundancy in the reaching movement, without instruction to do so.

It is also observed that Subjects 1 and 3 showed differences in movement patterns between the Pre-Test: Free and Post-Test: Free phases. The direction of this change was the same as those observed between the Pre-Test: Free and In Robot phases. This suggests that the change in condition (Free to Robot) itself changed how the subjects moved —even when compared to a normal "out of robot" movements. Whilst still under experimental conditions, it is noted that this represents a change from other experiments involving force fields, in which the Free condition is rarely considered.

B. Implications for Neurorehabilitation

These results present some key suggestions for implementations of such strategies in neurorehabilitation. It is clear that, like many neurorehabilitation strategies, the approach presented within this work did not uniformly affect all subjects. This is a trend which is likely to continue if this was to be applied in a rehabilitation context, especially given the variety of presentation of neurologically disabled subjects.

A key goal of neurorehabilitation, especially within the use of robotic devices, is to ensure that the improvements seen within the training regime generalise to activities of daily living. The results here suggest some promise that they may, with movement patterns changing between the Pre-Test and Post-Test Free reaching phases. Although this is not necessarily representative of leaving the clinic (or, in this case, experimental environment), it does suggest some promise in these approaches affecting the movement patterns when decoupled from the rehabilitative device.

C. Avenues of Future Research

These results are preliminary and do not provide any conclusive evidence as to the effectiveness of this approach. However, some indication of future work can be seen.

It is possible that a stronger field may lead to larger changes in movement patterns. Balancing this, however, is the underlying principle that the generalisation of such movements to other environments may not be preserved as the subjects perceive a significant difference between this and the other environments. This is similar to the conclusions drawn in [26], who suggest that 'too large' a difference results in a change of strategy (in [26], it is a change in reliance in the feedback mechanism). It is clear, however, that all subjects were aware of the changes of environment used during the intervention phase, and thus the experiment was not successful in 'subtle encouragement' of changes in movement patterns. This may also be investigated, potentially with longer intervention phases and with a larger subjects cohort.

Furthermore, different shaping control force-fields may be introduced, which may take into account additional influences —such as the biomechanical properties of the human. This may allow for more uniform response from the subjects within any particular experiment if a suitable field significantly affecting each cost function is constructed.

VI. Conclusion

This preliminary work explored the use of a change in dynamics to change the movement patterns of healthy subjects, resulting in dynamics which encouraged increased abduction at the shoulder whilst reaching forward. The results suggest that movement patterns can be affected by such an indirect shaping strategy, even if the subjects are unaware that a change in movement pattern is the desired objective. However, significant additional study is required to draw strong conclusions, or before such an approach can be considered for robotic neurorehabilitation.

References

[1] M. F. Levin, "Interjoint coordination during pointing movements is disrupted in spastic hemiparesis," *Brain*, vol. 119, no. 1, pp. 281–293, 1996.

[2] T. Sukal-Moulton, K. J. Krosschell, D. J. Gaebler-Spira, and J. P. Dewald, "Motor impairments related to brain injury timing in early hemiparesis. part II: abnormal upper extremity joint torque synergies," *Neurorehabilitation and Neural Repair*, vol. 28, no. 1, pp. 24–35, 2014.

[3] A. C. Lo, P. D. Guarino, L. G. Richards, J. K. Haselkorn, G. F. Wittenberg, D. G. Federman, and others., "Robot-assisted therapy for long-term upper-limb impairment after stroke," *The New England Journal of Medicine*, vol. 362, no. 19, pp. 1772—-1783, 2010.

[4] J. Mehrholz, M. Pohl, T. Platz, J. Kugler, B. Elsner, J. Mehrholz, M. Pohl, T. Platz, J. Kugler, and B. Elsner, "Electromechanical and robot-assisted arm training for improving activities of daily living, arm function, and arm muscle strength after stroke (Review)," *Cochrane Database of Systematic Reviews*, no. 9, 2018.

[5] V. S. Huang and J. W. Krakauer, "Robotic neurorehabilitation: A computational motor learning perspective," *Journal of NeuroEngineering and Rehabilitation*, vol. 6, no. 1, pp. 1–13, 2009.

[6] N. Jarrassé, T. Proietti, V. Crocher, J. Robertson, A. Sahbani, G. Morel, and A. Roby-Brami, "Robotic exoskeletons: a perspective for the rehabilitation of arm coordination in stroke patients," *Frontiers in Human Neuroscience*, vol. 8, p. 947, 2014.

[7] E. Todorov and M. I. Jordan, "Optimal feedback control as a theory of motor coordination," *Nature Neuroscience*, vol. 5, no. 11, pp. 1226–1235, 2002.

[8] E. Todorov, "Optimality principles in sensorimotor control," *Nature Neuroscience*, vol. 7, no. 9, pp. 907–915, 2004.

[9] E. Guigon, P. Baraduc, and M. Desmurget, "Computational Motor Control: Redundancy and Invariance," *Journal of Neurophysiology*, vol. 97, no. 1, pp. 331–347, 2007.

[10] Y. Uno, M. Kawato, and R. Suzuki, "Formation and Control of Optimal Trajectory in Human Multijoint Arm Movement," *Biological Cybernetics*, vol. 61, no. 2, pp. 89—-101, 1989.

[11] I. Wilms and H. Mala, "Indirect versus direct feedback in computer-based Prism Adaptation Therapy," *Neuropsychological Rehabilitation*, vol. 20, no. 6, pp. 830–853, 2010.

[12] A. J. McMorland, K. D. Runnalls, and W. D. Byblow, "A Neuroanatomical Framework for Upper Limb Synergies after Stroke," *Frontiers in Human Neuroscience*, vol. 9, no. February, pp. 1–6, 2015.

[13] B. Bobath, *Adult Hemiplegia: Evaluation and Treatment*, 3rd ed. Elsevier, 1990.

[14] N. Bernstein, *The Coordination and Regulation of Movements*. Oxford : Pergamon Press, 1967.

[15] T. Kang, J. He, and S. I. Tillery, "Determining natural arm configuration along a reaching trajectory." *Experimental Brain Research*, vol. 167, no. 3, pp. 352–361, 2005.

[16] J. Diedrichsen, O. White, D. Newman, and N. Lally, "Use-Dependent and Error-Based Learning of Motor Behaviors," *Journal of Neuroscience*, vol. 30, no. 15, pp. 5159–5166, 2010.

[17] G. Thielman, "Rehabilitation of reaching poststroke: a randomized pilot investigation of tactile versus auditory feedback for trunk control," *Journal of Neurologic Physical Therapy*, vol. 34, no. 3, pp. 138–144, 2010.

[18] V. Crocher, J. Fong, M. Klaic, D. Oetomo, and Y. Tan, "A tool to address movement quality outcomes of post-stroke patients," in *Replace, Repair, Restore, Relieve–Bridging Clinical and Engineering Solutions in Neurorehabilitation*. Springer, 2014, pp. 329–339.

[19] E. B. Brokaw, T. Murray, T. Nef, and P. S. Lum, "Retraining of interjoint arm coordination after stroke using robot-assisted time-independent functional training," *The Journal of Rehabilitation Research and Development*, vol. 48, no. 4, p. 299, 2011.

[20] E. B. Brokaw, P. S. Lum, R. A. Cooper, and B. R. Brewer, "Using the kinect to limit abnormal kinematics and compensation strategies during therapy with end effector robots," *IEEE International Conference on Rehabilitation Robotics*, 2013.

[21] V. Crocher, N. Jarrassé, A. Sahbani, A. Roby-Brami, and G. Morel, "Changing human upper-limb synergies with an exoskeleton using viscous fields," in *2011 IEEE International Conference on Robotics and Automation*. IEEE, 2011, pp. 4657–4663.

[22] T. Proietti, E. Guigon, A. Roby-Brami, and N. Jarrassé, "Modifying the upper-limb inter-joint coordination by training with a robotic exoskeleton,," *Journal of Neuroengineering and Rehabilitation*, vol. 14, p. 55, 2017.

[23] M. D. Ellis, C. Carmona, J. Drogos, and J. P. Dewald, "Progressive abduction loading Therapy with horizontal-Plane Viscous resistance Targeting Weakness and Flexion synergy to Treat Upper limb Function in chronic hemiparetic stroke: a randomized clinical trial," *Frontiers in Neurology*, vol. 9, p. 71, 2018.

[24] S. K. Subramanian, C. L. Massie, M. P. Malcolm, and M. F. Levin, "Does provision of extrinsic feedback result in improved motor learning in the upper limb poststroke? a systematic review of the evidence," *Neurorehabilitation and Neural Repair*, vol. 24, no. 2, pp. 113–124, 2010.

[25] J. Fong, V. Crocher, Y. Tan, D. Oetomo, and I. Mareels, "EMU: A transparent 3D robotic manipulandum for upper-limb rehabilitation," *IEEE International Conference on Rehabilitation Robotics*, pp. 771–776, 2017.

[26] S.-H. Zhou, D. Oetomo, Y. Tan, I. Mareels, and E. Burdet, "Effect of sensory experience on motor learning strategy," *Journal of Neurophysiology*, vol. 113, no. 4, pp. 1077–1084, 2014.