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Influence of Visual Feedback in the Regulation of Arm Stiffness Following Stroke

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Abstract— **Stroke survivors strongly rely on visual feedback to control their movements, since segmental reflexes are characterized by an inherent hyper-excitability. To test the effect of visual feedback on the modulation of arm stability we estimated the stiffness of the paretic arm in nine stroke survivors during robot mediated therapy, where subjects trained with and without vision. While several studies found a negligible effect in unimpaired individuals, our results highlighted a marked reduction of stroke survivors' arm stiffness in absence of visual feedback.**

I. Introduction

VISUAL feedback (VF) is often employed by intact individuals for the direct modulation of joint's torque [1], and its effect on the modulation of stiffness is usually negligible [2] or small [3]. On the other hand, it has been suggested that in addition to motor coordination disorders, stroke survivors might be affected by sensory organization disorders. This arose from the experimental observation that the reliance of stroke survivors on VF is quite important [4].

Indeed, the reflexive feedback mechanism, which is believed to be responsible for the maintenance of limb stability by modulating muscle stiffness, is compromised. It is known that stroke survivors exhibit hyper-excitability of reflexes, which increases the limb stiffness [5] and might be responsible for the scarce coordination of movements. Moreover, it has been demonstrated that a cerebro-vascular accident reduces the cerebral resources available, hence forcing individuals to use different pathways to control their movements.

In this work we investigated the influence of VF on the modulation of arm stiffness during sessions of robot-mediated therapy. We measured subjects' arm stiffness during movement on a trial by trial basis, where VF was either presented or precluded within whole blocks of trials. We estimated a systematic decrease of limb stiffness when VF was suppressed, and subjects were forced to rely more on proprioceptive feedback.

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II. Methods

To estimate the endpoint stiffness of stroke survivors' paretic arm during robot-mediated therapy, we employed a Time-Frequency domain identification technique [6]. Subjects were trained using a hitting task over a large workspace, while a robot provided aiding forces to reach the targets. A sudden drop of aiding force in the proximity of each target allowed for a suitable perturbation to be used in the estimation of arm stiffness. The estimation process can be easily implemented in the rehabilitation process and is mostly transparent to the subject.

A) *Subjects*

Nine chronic stroke survivors (2 males and 7 females) participated in the study after signing informed consent conform to the ethical standards of the Helsinki declaration. The characteristics of the subjects are described in Tab. I

B) *Robot mediated therapy*

Subjects were seated grasping the handle of the manipulandum "Braccio di Ferro" [7] with their impaired hand. A custom made cast limited the wrist movement while a harness connected to the chair eliminated the translation of the shoulder allowing only the horizontal flexion/extension of shoulder and elbow. The arm was allowed to slide on a low friction surface eliminating the influence of gravity. Thirteen targets (diameter 2 cm) were located at three concentric circles (A, B, C) centered at the shoulder (fig.1). Visual feedback was presented by means of a 19" monitor positioned vertically in front of the subject at a distance of about 1 m.

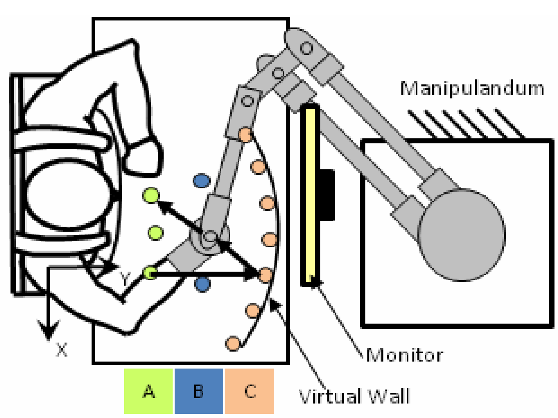

Figure 1 Experimental Setup

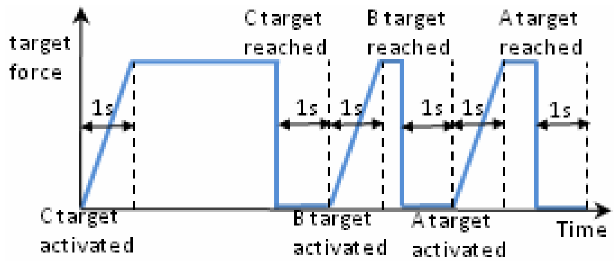

Figure 2 Force Field, Structure of the basic trial.

From one of the starting positions on 'A', one of the seven 'C' targets was randomly selected (fig.1); the aiding force was turned on; an acoustic feedback was given synchronously with the reaching of the target while the aiding force was suddenly turned off for a time interval of 1s (fig. 2). The same process was repeated transitioning from 'C' to a random target on 'B', and subsequently form 'B' to a random target in 'A'. These three steps, representing one trial, were repeated so to have three presentations of each one of the seven 'C' targets, for a total of sixty-three movements per block.

The rehabilitation process involved 10 sessions where several blocks were presented to the subject with different aiding forces that decreased within a session as a function of the subject improvement. Each session started with the same initial force that was selected by the therapist in the first block of the first session as the minimal force allowing the subject to initiate the movement. For each aiding force level, two blocks of trial were presented. For a whole block VF was either present or suppressed. The presentation order of VF was random. Vision was precluded by blindfolding the subject so to suppress also the vision of the limb. The overall duration of the sessions ranged from 45 to 75 minutes. After the first 4 blocks, the therapist could decide to extend each session with additional blocks characterized by lower levels of force in accordance with the subject capability.

C) *Time-Frequency Domain*

The sudden drop of the assistive force as describe in Fig.2 elicits a recoil movement $\overrightarrow{\partial X}(t)$ that can be represented using a second order model with time-varying coefficients, namely:

$$I(X,t)\overrightarrow{\partial \ddot{X}}(t)+B(\dot{X},X,t)\overrightarrow{\partial \dot{X}}(t)+K(\ddot{X},\dot{X},X,t)\overrightarrow{\partial X}(t)=0 \quad (1)$$

While the inertia I is a geometrical characteristic of the limb, stiffness K and damping B depend on passive joint properties, volitional interventions, and the reflex pathways responsible for the alteration of muscle activation. As such, stiffness and damping provide a complete characterization of the mechanical properties of the limb that can be directly modulated by neural activities.

Given the duality between the time and frequency domain, B and K can be estimated by examining the natural frequencies and vibrational modes of the system [8]. Therefore, (1) can be decoupled in a set of mutually independent equations whose coefficients are functions of the time-varying resonant frequencies of the system. The decoupling of (1) is obtained in 2 steps.

TABLE I SUBJECT CHARACTERISTICS

	Age	DD	FM before	FM after	Ash	G	E	PH	AF
S1	72	28	6	8	3	M	I	L	20
S2	69	25	12	18	1+	F	I	R	12
S3	57	40	17	21	3	M	I	L	9
S4	34	24	13	23	1+	F	I	R	9
S5	30	12	6	9	2	F	I	L	6
S6	46	26	6	13	2	F	H	L	8
S7	55	76	36	41	1	F	H	L	4
S8	59	39	5	8	3	F	I	R	20
S9	53	39	41	45	1	F	H	R	5

Subjects data. Age: years. DD= duration of disease (months) FM = upper arm Fugl- Meyer score, max 66/66; before, after and after three months with respect to the robot therapy sessions, Ash= Ashworth score, Gender: M=male, F=female; E= Etiology: I=ischemic, H= Hemorrhagic; PH=paretic hand: L=Left, R=Right; AF=level of assistive force at which we estimated the stiffness [N]

In the first step, the inertial parameters of the subjects' arm with respect to the shoulder and elbow joints were estimated using a regressive equation, function of anthropometric parameters [9]. Hence, the endpoint inertial matrix was obtained via a Jacobian transformation from the joint space to the Cartesian space [10]. The inertial matrix is real and positive definite; hence, it is invertible and admits real squared roots. Therefore, by pre- and post-multiplying I, B, and K by the matrix $I^{-\frac{1}{2}}$ we obtain a normalized system which is symmetric and real [8], namely:

$$\overrightarrow{\partial \ddot{Y}}(t)+\tilde{B}\vec{\dot{Y}}(t)+\tilde{K}\vec{Y}(t)=0 \quad (2)$$

The second step of the decoupling entails the pre- and post- multiplication of each matrix of (2) by the eigenvector matrix P of $\tilde{K}$ which represents the directions of the vibrational modes in the Cartesian space [8], hence obtaining the decoupled system:

$$\overrightarrow{\partial \ddot{Y}}(t)+diag[2\Gamma]\vec{\dot{Y}}(t)+diag[\eta^2]\vec{Y}(t)=0 \quad (3)$$

In general, the normalized resonant frequency $\eta^2(t)$ and normalized damping factor $\Gamma(t)$ are time-varying and can be estimated as follows [6]:

$$\Gamma(t)=-\sigma-\frac{\dot{\omega}_i}{2\omega_i};\ \eta^2(t)=\omega_i^2+\sigma^2+\frac{\sigma\dot{\omega}_i}{\omega_i}-\dot{\sigma} \quad (4)$$

where

$$\sigma(t)=\frac{d}{dt}\ln A(t)=\frac{\dot{A}(t)}{A(t)} \quad (5)$$

The instantaneous amplitude $A(t)$ and the instantaneous resonant angular frequency $\omega_i(t)$ can be obtained from a spectrogram of the recoil movement $\overrightarrow{\partial X}(t)$ [6].

To obtain the eigenvector matrix ($P \in \Re$), we can recall that the general solution of (1) is the super-imposition of all the vibrational modes:

$$\overrightarrow{\partial X} = \vec{s}_1 + \vec{s}_2 = \begin{Bmatrix} s_{1_1} \\ s_{1_2} \end{Bmatrix} + \begin{Bmatrix} s_{2_1} \\ s_{2_2} \end{Bmatrix} \tag{6}$$

$$\overrightarrow{\partial X} = C_1 e^{\alpha_1 t} \cos(\omega_1 t - \psi_1) \begin{Bmatrix} p_{1_1} \\ p_{1_2} \end{Bmatrix} + C_2 e^{\alpha_2 t} \cos(\omega_2 t - \psi_2) \begin{Bmatrix} p_{2_1} \\ p_{2_2} \end{Bmatrix} \tag{7}$$

where $\vec{p}_j$ are the eigenvectors (i.e. the directions of the vibrational modes in the Cartesian space) of matrix $\tilde{K}$. Since each mode is associated with a specific resonant angular frequency $\omega_i(t)$, we can identify each mode by band-pass filtering $\overrightarrow{\partial X}(t)$. Subsequently, since $\vec{p}_1$ and $\vec{p}_2$ are mutually orthogonal, using a single value decomposition (SVD) between s_{1_1} and s_{1_2} we can identify $\vec{p}_1$ and its orthogonal $\vec{p}_2$. Thus, after having obtained $A(t)$, and $\omega_i(t)$ from the spectrogram of $\overrightarrow{\partial X}(t)$, and the eigenvector matrix P from the aforementioned filtering process it is possible to reconstruct B and K using equations (1-5).

III. RESULTS

Since in the first two blocks, the subject might still get acquainted with the exercise, we estimated the stiffness in the second and third block of each session. The presentation of the blindfolded blocks was randomized among sessions and subjects, and the aiding force in the blocks is reported in Tab. I. Stiffness estimation was considered at 200 ms after the perturbation onset. In this timeframe, stiffness is a function only of the intrinsic stiffness of the muscle and reflexes, with no contribution of voluntary control. We found a good repeatability of the estimated stiffness values for each target of the same block, and a systematic decrease in stiffness in the blindfolded condition (Fig. 3).

In order to globally characterize the stiffness throughout the workspace, we evaluated the determinant and the maximum eigenvalue of the stiffness matrix. The determinant provides the area of the stiffness ellipses represented in fig.3.

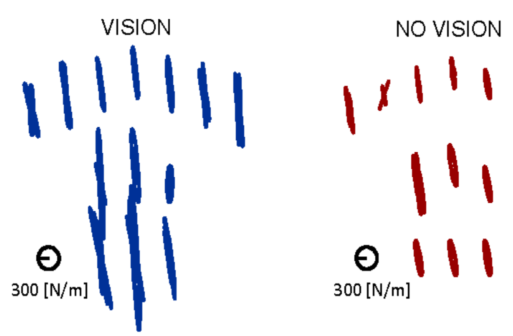

Figure 3 Stiffness estimation for S3, during session 6. Three stiffness estimations were computed for each of the 13 targets. It is evident how the suppression of visual feedback decreased the magnitude of arm stiffness throughout the workspace

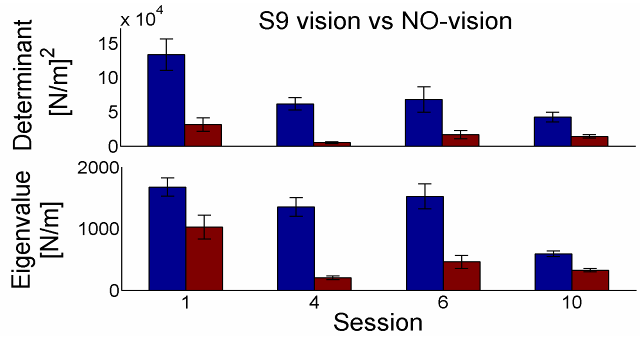

Figure 4 Comparison for subject S9 between the stiffness metrics with vision (BLUE) and without vision (RED) at the same level of assistive force (5N) reported in Tab.I. Error bars are SE. For significant statistical differences in the metrics populations between vision and no-vision see Table II.

This metric gives an idea of the overall co-contraction level of the subject while performing the task. The maximum eigenvalue of the stiffness matrix indicates the magnitude of stiffness in the direction on maximum resistance. These two parameters provide different information. Indeed, there are locations in the workspace, where the subject tunes the stiffness in a particular direction, rather than stiffening the whole arm, which instead would increase the area of the ellipses by expanding it in different directions.

We considered the averages of the two aforementioned metrics among the 13 targets where we estimated the stiffness. Session after session, we compared the two metrics in the two conditions (vision vs. blind), observing a consistent decrease in stiffness in the blind condition (Fig. 4, 5). This was also confirmed by a series of one-way ANOVAs, with subjects as random factor. The decrease in stiffness in the blindfolded blocks is statistically significant for the sessions we analyzed, except the last one, where the effect of the training modified permanently the stiffness modulations.

In previous publications, we reported the average speed of reaching, as a function of the different sessions [7]. Previous data point-out an increase in average speed due to the training. Such increase in speed would actually tend to increase the intrinsic stiffness at the joints in unimpaired individuals [11]. The result found here confirms that the decrease in arm stiffness is not a byproduct of the change in reaching speed, but is an independent change of a control variable, tending to diminish the hyper-tonicity of the limb.

The training has a statistical effect in diminishing the stiffness both with and without vision. This is confirmed by a multi-factorial ANOVA between the first and last session. Training and VF were considered as fixed factors and the subjects as a random factor. The decrease in stiffness due to the training is statistically significant. Furthermore, the stiffness while training without vision is systematically lower than when training with VF (Tab. III). The stiffness in the two conditions converges at the end of the training where no statistical difference is found.

TABLE II STIFFNESS STATISTICAL COMPARISON BETWEEN REACHING WITH AND WITHOUT VISUAL FEEDBACK WITHIN SESSION

session	Determinant		Max Avg. Eigenvalue	
	F(1,8)	p	F(1,8)	p
1	8.883	0.0176	8.013	0.0221
4	9.911	0.0136	9.224	0.0161
6	7.710	0.0241	5.850	0.0420
10	2.264	0.1709	4.288	0.0721

Statistical significance between the metrics used to represent stiffness with and without VF.

IV. CONCLUSION

This study tested the effect of motor coordination and sensory organization on the modulation of limb mechanics in stroke survivors. We tested the modulation of arm stiffness during 10 sessions of robot- mediated therapy using a time-frequency technique. Based on the experimental observation that the dependence of visual feedback post-stroke is quite high [4], we hypothesized that the suppression of such reliable sensory feedback during the exercise would force the trainees to utilize their proprioceptive feedback, trying to regulate their feedback gain compromised by the cerebro-vascular accident.

The decrease in stiffness is often used in several robotic applications where the uncertainty of the environment precludes a careful planning of the end-effector trajectory. Since the risk of collisions increases, a lower stiffness of the arm minimizes the reaction force caused by collisions, decreasing damage. This strategy seems appealing for decreasing the hyperactive activity of reflexes, which play a crucial role in the modulation of stiffness.

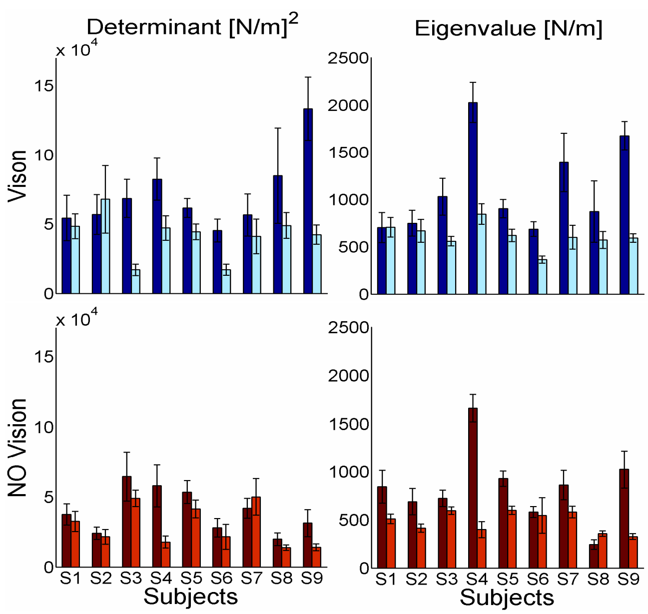

Figure 5 Comparison between stiffness metrics estimated in the first and last session. The first row depicts the first session (Dark BLUE) vs the last session (Light BLUE) with vision. The second row presents the first session (Dark RED) vs the last session (Light RED) without vision. We can notice how stiffness decreases with the treatment both with and without VF. Furthermore, we can notice that the stiffness metrics are smaller without visual feedback. Error bars are SE. For significant statistical differences in the metrics populations between the first and last session see Table III.

TABLE III THREE WAY ANOVA WITH SUBJECT AS A RANDOM FACTOR BETWEEN THE FIRST AND LAST SESSION

source	df	Determinant		Max Avg. Eigenvalue	
		F(1,df)	p	F(1,df)	p
Subject	8	0.76	0.6508	2.62	0.1854
Session	1	6.12	0.0384	11.74	0.0090
Vision	1	6.74	0.0318	15.08	0.0047
Subject * Session	8	1.59	0.2623	2.60	0.0995
Subject * Vision	8	1.75	0.2224	0.38	0.9041
Session * Vision	1	4.69	0.0623	1.97	0.1983

Repeating the exercise allowed an increase in motor coordination decreasing the arm stiffness throughout the training. However, when tested without VF the arm stiffness of the subjects was lower within the same session. This behavior was statistically significant among subjects throughout the therapeutic intervention and evened out towards the end of the training, where subjects regained more control over the modulation of proprioceptive feedback. Therefore, in spite of what observed for unimpaired individuals, VF influences the regulation of arm stiffness in stroke survivors to a greater extent.

These results are relevant for planning therapeutic interventions that could help a broad population of stroke survivors to improve their arm control and sensorimotor integration.

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