Title page

Rhythmic robotic training enhances motor skills of both rhythmic and discrete upper-limb movements after stroke – A longitudinal pilot study

Short title: Rhythmic training after stroke

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Abstract

Discrete and rhythmic movements are two fundamental motor primitives being, at least partially, controlled by separate neural circuitries. After a stroke, both primitives may be impaired in the upper-limb. Currently, intensive functional movement therapy is recommended after stroke, but it is mainly composed of discrete movements. No recommendation is made for the specific training of rhythmic movements. However, if they form two different primitives, both should receive a specific training in order to recover the complete motor repertoire, since many daily live movements are composed with both of them.

This paper reports the effects of a pure unilateral rhythmic movement therapy on motor performance, after stroke. Thirteen chronic stroke patients participated to this longitudinal pilot study. They were assessed twice before the therapy in order to validate their chronic state, and twice after the last session in order to establish the short and long term effects of the therapy. The therapy itself was composed of 12 sessions spread over one month. The exercises consisted in performing straight or circular rhythmic movements, while receiving assistance-as-need through a robotic device.

Short- and long-term improvements were observed in rhythmic movements regarding smoothness, velocity and harmonicity. More surprisingly, some transfer occurred to the untrained discrete movements. This finding disputes previous studies that reported no transfer from rhythmic to discrete movements with healthy subjects.

Keywords: Stroke, Rhythmic movements, Robotics, assistive electronic technologies, Motor Learning

Text

Introduction

A movement is said to be discrete if it is executed between two different postures with both zero velocity and acceleration. In contrast, rhythmic movements are periodic and display an acceleration peak at the zero-velocity movement reversal (Buchanan, et al., 2006; Hogan & Sternad, 2007; Goto, et al., 2014). Literature in motor control established that these two movements form two different primitives in the motor repertoire (Guiard, 1993; Schaal, et al., 2000; Sternad, et al., 2000; de Rugy & Sternad, 2003; Spencer, et al., 2003; Schaal, et al., 2004; van Mourik & Beek, 2004; Smits-Engelsman, et al., 2006). For instance, imaging data in humans and animals showed that they recruit distinct neural circuitries – at least partially (Schaal, et al., 2004; Hira, et al., 2015). Behavioural data with healthy participants revealed that there is no learning transfer from rhythmic to discrete movements and few from discrete to rhythmic movements (Ikegami, et al., 2010; Howard, et al., 2011).

After a stroke, the execution of both movement types is potentially impaired (Gowland, et al., 1992; Krebs, et al., 1999; Rohrer, et al., 2002; Dipietro, et al., 2009; Hogan & Sternad, 2009; Zehr, et al., 2012; Simkins, et al., 2013; Gilliaux, et al., 2012; Gilliaux, et al., 2014; Leconte, et al., 2016). Although there is a consensus about the necessity to deliver intensive functional movement training during post-stroke therapy (Winstein, et al., 2016), much fewer studies have explored specific training of rhythmic movements (Whitall, et al., 2000; Luft, et al., 2004; Hesse, et al., 2005; Diserens, et al., 2007; Whitall, et al., 2011), and this – to the best of our knowledge – is not frequently performed in daily practice. A noticeable exception is bilateral arm cycling, but the functional transfer of this movement is limited due to the strong kinematic constraints being imposed by the device mechanical topology. However, if they form two different primitives, both discrete and rhythmic movements should receive a specific training in order to recover the complete motor repertoire, including sophisticated activities blending them together, like wiping a table or playing music (Sternad & Dean, 2003).

In a recent paper, we established that discrete movements might be more impaired than rhythmic ones after stroke (Leconte, et al., 2016). Training rhythmic movements might thus be beneficial not only for improving their own performance but also to leverage the execution of discrete movements through combined exercises (Sternad, et al., 2000; Sternad & Dean, 2003).

Previous studies reported that post-stroke rhythmic movement training might lead to motor improvements in the upper-limb, although the exact impact of rhythmicity was not specifically highlighted. For instance, (Bütefisch, et al., 1995; Hesse, et al., 2005) focused on training intensity in order to enhance motor control. (Whitall, et al., 2000; Luft, et al., 2004; Stinear & Byblow, 2004; Diserens, et al., 2007) relied on bilateral training, so that this aspect might also play a significant role in the reported improvements. (Whitall, et al., 2011) compared bilateral arm training with auditory cueing (BATRAC) to dose-matched therapeutic exercises and concluded that one was not superior to the other, although the adaptations in brain activation were greater after BATRAC. Auditory cueing can also play a role in the improvements made during BATRAC, since this is known to enhance movement kinematics after stroke (Thaut, et al., 2002; Thaut & Abiru, 2010). In summary, these studies suggested that rhythmicity might offer some therapeutic benefits after stroke, although the reported improvements might also be influenced by other aspects of the protocols.

Therefore, the goal of the present paper is to assess the impact of a purely unilateral rhythmic movement training on motor performance after stroke. Although bilateral training appeared to be a powerful modality for post-stroke therapies (Mudie & Matyas, 2000), we focused here on unilateral training in order to avoid interferences from the specific inter-hemispheric neural mechanisms being putatively recruited during bilateral training (Gassert & Dietz, 2018). Moreover, we investigated the impact of our therapy not only regarding rhythmic movements themselves, but also regarding a possible transfer to discrete movements. More precisely, we tested whether rhythmic movement therapy enhances not only rhythmic movement features but also those of discrete movements, or not. The later would support behavioral experiments reporting no learning transfer with healthy subjects performing unilateral movements (Ikegami, et al., 2010; Howard, et al., 2011). In contrast, the former would support the claim that rhythmic movement training might be used to leverage the execution of the more impaired discrete movements, possibly because some neural overlap exists between rhythmic and discrete movement control after stroke.

To test these hypotheses, we built a longitudinal pilot study where chronic stroke patients received a unilateral rhythmic movement therapy via a robotic device that delivered assistance-as-needed. We report the evolution regarding several critical movement features (smoothness, velocity, amplitude, and accuracy) as short- and long-term effects following the therapy in performing both rhythmic and discrete movements with and without the robot.

Materials and methods

Participants

Fourteen chronic stroke patients were recruited for this study. Patients were eligible for the study if (i) they had suffered from a non-cerebellar stroke more than 6 months before the first assessment, (ii) they could understand the task instructions, (iii) they did not suffer from severe visual impairments or severe neuropsychological impairments like aphasia, attention deficit or neglect, and (iv) they had an active shoulder range of motion above 20° of flexion and abduction. One patient faced health issues during the therapy and had to leave the study. Her data were withdrawn for the database and analyses. Another patient did not show up for the last assessment, so that the corresponding data is missing.

Moreover, thirteen age-matched healthy subjects were recruited in order to collect normative data for comparisons with the patients' performance across the therapy. Patient and healthy subject characteristics are reported in Table 1. It also reports the Fugl-Meyer assessment of the upper extremity (FMA-UE) clinical scale (Fugl-Meyer, et al., 1975) for each patient as collected during the first assessment session (A1).

All subjects gave written informed consent prior participating to the study, which was approved by the ethical committees of the Université catholique de Louvain (Comité d'Ethique hospital-facultaire). This study has been registered on clinicaltrial.gov number NCT02139553.

Experimental setup

All the experiments were performed with the participant sitting on a chair in front of a planar robot. The robot used during this study was the REAplan (Figure 1A). This upper-limb end-effector robot can accurately measure the movement kinematics and deliver forces (i.e., haptic feedback) in both dimensions of the movement plane using an actuated handle. Previous studies validated its use as a rehabilitation robot (Gilliaux, et al., 2012; Gilliaux, et al., 2014; Leconte, et al., 2016; Leconte & Ronsse, 2016). The movement plane is adjustable in height, and the end-effector handle is equipped with force sensors in order to close the haptic loop. The exercises and the visual feedback given to the participants were projected on a vertical screen placed behind the horizontal movement plane.

Therapy

Patients practiced rhythmic movements with this robot during 12 sessions of 18 minutes spread over one month, i.e. approximately 3 sessions per week. This induced a movement intensity similar to many previous studies reporting post-stroke robotic interventions (Kwakkel, et al., 2008; Veerbeek, et al., 2017). Each rehabilitation session started with a short assessment in order to quantify the patient's daily level of performance. The patients were asked to draw ten circles while holding the robot handle at a comfortable speed and amplitude without stopping (such as steering in a pot). The robot was controlled to be transparent, while the algorithm computed the average amplitude, velocity and center of the circles as explained in (Leconte & Ronsse, 2016). These features were then used as baseline values during the six exercises of that particular therapy session.

The exercises of the therapy session consisted of four rhythmic, straight, back-and-forth movements between two targets (Figure 1C - 1 to 4) and two rhythmic circular movements, which had to be executed inside of a 3-cm wide track (Figure 1C - 5 and 6). The actual position of the patient was displayed as a circular dot. If the patient moved slower than the desired velocity computed during the assessment phase, the targets or the track became orange, then red (if more than 10% below the desired velocity); otherwise, it remained green. During the 10 first seconds of the task, the robot was set in transparent mode. Next, the robot started to deliver performance-based assistance (see Figure 2), triggered as follows:

- If the patient was moving too slowly, a velocity assistance was triggered, as a tangential force along the desired path;
- If the patient performed too small movements (i.e., did not manage to reach the targets or to stay inside the track), an amplitude assistance was triggered, as a force being phase-synched with the hand acceleration, i.e. pushing the hand to the targets or outwards;
- Finally, if the movement was detected to be too jerky, a smoothness assistance was delivered. The smoothness assistance rendered the feeling of a damped-spring connected between the actual position of the patient (p_{pat} in Figure 2) and a smoother version of it (p_{osc} in Figure 2), which was computed in real time by an adaptive oscillator extracting the movement's main harmonic. All mathematical foundations about the assistance forces and feedback given to the patients can be found in (Leconte & Ronsse, 2016).

The order of the exercises was randomized. Each exercise was executed during 60 seconds and was repeated 3 consecutive times. A feedback sentence was also displayed on the screen as a function of the average performance. The patients could rest for two minutes if needed between each trial. Each patient was thus active for 18 minutes for each of the training sessions, but the whole therapy session could last up to one hour if all possible resting periods were taken.

Assessment

Chronic stroke patients were assessed twice (A1 and A2) before the first session of the therapy in order to measure whether their motor performance had reached a steady state, i.e. displayed no more natural or therapeutically-induced evolution. These two first assessments were conducted at least one month apart from each other. After having completed the 12 training sessions, patients were evaluated a third time (A3) in order to assess the short-term evolution in their motor performance due to the intervention. Finally, patients were assessed a last time (A4), three months after the last session of the therapy, in order to assess the long-term retention of the intervention. Patients were asked to maintain the same intensity of conventional therapy over the 5 months of the study. However, none of them executed rhythmic upper-limb exercises during the conventional therapy. We exposed the thirteen age-matched control subjects to a single assessment session only in order to collect normative data with a healthy population.

The assessment sessions consisted of a robotic tests with the REAplan in order to capture the ability to perform both rhythmic and discrete movements. In all the tasks being performed in these assessment blocks, the robot was used as a measurement device only, i.e. was controlled to be transparent in order to minimize the impact on the user's movement. Participants performed six different tasks with each arm to capture fundamental rhythmic and discrete movements (see Figure 1B). Moreover, the rhythmic tasks were tested with and without visual targets, since our previous results revealed a potential difference in impairment in these two contexts (Leconte, et al., 2016):

- R-T: rhythmic back-and-forth movements between two targets of 7x7cm², separated from each other by 14.5cm – 15 cycles
- R-NT: same task but with the targets disappearing after 5 seconds – 15 cycles after these 5 initial seconds
- C-T: rhythmic circular movements performed around a circular disc with a diameter of 12cm. With the right arm, participants had to turn clockwise, with the left arm counterclockwise – 10 circles

- C-NT: same task but the target disc disappeared after 5 seconds – 10 circles after these 5 initial seconds
- D-T: back-and-forth movements between two small targets (0.7x0.7cm² separated from each other by 18cm) forcing cinematically discrete movements – 10 back-and-forth movements
- D-BT: back-and-forth movements between two targets similar as for the R-T task. In this condition, participants were specifically requested to stay inside the previous target and to wait for an auditory cue before moving to the opposite target – 10 back-and-forth movements

The width W and amplitude A of the targets were determined according to Fitt's law (Fitts, 1954) in order to have an index of difficulty (ID) equal to 2.5 in the tasks with large targets and a ID equal to 5 in the D-T task ($ID = \log 2\left(\frac{2A}{W}\right)$). Previous studies established that executing back-and-forth movements between two targets without forcing the participant to stop inside the target with low ID induces cinematically rhythmic movements, i.e. movements with maximal acceleration at the movement reversal. In contrast, high ID induces cinematically discrete movements with zero acceleration at the movement reversal (Buchanan, et al., 2006; Guiard, 1993).

Note that this paper reports only the results of the paretic arm of post-stroke patients and the dominant arm of healthy subjects.

Data processing and kinematic indices

The raw position trajectories of the handle during the therapy and assessment sessions were recorded with a sampling frequency of 125 Hz. They were filtered backwards and forwards using a second-order Butterworth filter with a cut-off frequency of 6 Hz. Next, the velocity, acceleration and jerk were obtained by successive numerical differentiation of the filtered position signal. Thereafter, these signals were cut into individual movements. Only the last eight movements of each trial were kept for analyses in order to focus on steady-state behavior only. This further eliminated the first rhythmic cycles, which could be governed by discrete primitives (van Mourik & Beek, 2004; Howard, et al., 2011).

For each movement, we computed the following metrics: the velocity peak (v_{max}), the dwell time ($dwell$) (not in D-BT task), the harmonicity index (H) (not in D-BT task), the spectral arc length ($SPARC$) and the accuracy at the movement reversal ($accuracy$, only in D-T and D-BT).

Dwell time is a specific landmark of discrete movements (Buchanan, et al., 2006; Hogan & Sternad, 2007; Sternad, et al., 2013), measuring the duration around the movement reversal during which no movement occurs, as a percentage of the whole movement duration. Concretely, we measured the time interval between the first time the movement speed went below 5% of the velocity peak and the acceleration below 5% of the acceleration peak of the preceding movement until the first time the velocity went above 5% of the velocity peak and the acceleration above 5% of the acceleration peak of the following movement. This metric was computed to assess kinematic evolutions of rhythmic and discrete movements.

The harmonicity index H, which is bounded between 0 and 1, provides an overview of the movement type produced by the participant during each task (Guiard, 1993; Buchanan, et al., 2006; Leconte, et al., 2016). The index requires measurement of the peak acceleration at movement reversal and normalizes it with the minimum acceleration between two consecutive acceleration peaks. If only one acceleration peak occurs at the movement reversal, H is set to 1. If the minimum acceleration is negative, it saturates to 0. Since a pure rhythmic movement displays a maximal acceleration at the movement reversal, its H index is close to 1. Discrete movements, on the other hand, have a zero acceleration at the movement reversal, so that the corresponding H index is equal to 0. This metric is not reported for the D-BT task, since participants were forced to stop inside the targets, so that H would systematically be equal to 0.

The $SPARC$ metric is a smoothness metric, recently developed by (Balasubramanian, et al., 2015). It is intended to be less sensitive to noise than other metrics and relies on a frequency analysis of the velocity profile by quantifying how close a signal is from a pure harmonic signal. Since the frequency spectrum of a jerky movement is richer than the one of a smooth movement – due to the large amount of submovements in its velocity profile – the corresponding $SPARC$ will be lower (i.e., more negative). In sum, higher $SPARC$ corresponds to smoother movement.

Finally, $accuracy$ is obtained by measuring the distance between the center of the targets and the actual position of the movement reversal.

Data analysis and statistics

All statistics were performed with JMP pro 12 software (SAS Institute Inc.). We performed statistics on the movement kinematics measured with the robot during the assessment sessions. For each task and for all abovementioned metrics, a mixed model was performed on the dataset. It contained the assessment number as a fixed effect and the participant number as a random effect. The models were solved using a "restricted maximum likelihood" method to estimate the variance parameters. The post hoc Tukey HSD test was used to compare the modalities of significant factors. Patient 9 was excluded from the analysis in the R-T, C-T, D-T and D-BT tasks since he was never able to reach the targets.

In order to compare the performance level reached by the patients after the therapy with the performance of a healthy population, we compared the results of the patients' third assessments with the results of the thirteen age-matched control subjects. Again, for each task and metric, a similar mixed model was computed to measure the effect of each participant's type (control or patient). The participant number was again set as a random effect.

Results

Statistics are reported in Table 2, and the most relevant data of rhythmic (R-T, C-T) and discrete (D-T and D-BT) assessment tasks are graphically reported in Figures 3 and 4, respectively.

Validity of longitudinal study

Patients were stable across the two first assessment sessions, thus fulfilling a criterion for the validity of a longitudinal study: the post-hoc Tukey tests between A1 and A2 never reached significance ($p>0.05$) for all tasks and metrics, except for the harmonicity index H of the C-NT task and for the accuracy during the D-T task. The latter is due to an outlier (patient 5), which was highly inaccurate during the first session and strongly improved during the second session.

Rhythmic movements got improved due to the therapy

Right after the therapy (A3), patients displayed significant improvements for almost all metrics measured from the rhythmic tasks. Patients moved faster and reached the same velocity as healthy subjects in the R-T and R-NT task. The harmonic nature of the movements was improved in the C-T, R-T and R-NT task (post-hoc Tukey tests of A1 vs A3 and A2 vs A3, all p's<0.05). It reached the same level as for healthy subjects in the C-NT and R-NT tasks. Finally, smoothness improved during the C-T, R-T and R-NT tasks ($SPARC$). The smoothness level reached the same level as for healthy subjects during the R-T and R-NT tasks. Most of these improvements were maintained at the three-month follow-up assessment (A4). Only the harmonicity during the R-NT task regressed back to the same level as during the pre-therapy assessment values.

The dwell time did not significantly evolve after the therapy, but the level reached during A3 was not significantly different from that of healthy subjects.

Discrete movements also improved, mainly regarding smoothness and speed

Interestingly, after this purely rhythmic therapy, patients also displayed a positive evolution in performing the discrete tasks, even if these movements were not specifically trained. Patients moved faster and movements were performed in a smoother way, at least in the D-BT task where the $SPARC$ metric improved. Moreover, this metric reached the same level as for healthy subjects. The improvements were maintained after 3 months for the D-BT task, while A4 was significantly higher than A1 and A2 during the D-T task.

In contrast, the level of accuracy did not evolve. Significance was never reached for post-hoc Tuckey tests between A2, A3 and A4. Regarding A1, the difference with the other sessions reached significance only for the D-T task. A deeper analysis highlighted that this was due to patient 5, who behaved as an outlier during the first session of this task, displaying a poor accuracy for that task and that day only.

Discussion

The aim of this study was to investigate whether a pure unilateral rhythmic movement training, after stroke, would (1) improve the performance of rhythmic movement execution and (2) trigger some transfers to the execution of discrete movements. This training relied on an assistive approach that we developed using adaptive oscillators. It provides an as-needed assistance force that continuously adapts to the pattern being performed and steered by the patient (Leconte & Ronsse, 2016). All features (i.e. velocity, smoothness, harmonicity) of the rhythmic movements improved after the therapy. More surprisingly, some discrete movement features, such as velocity and smoothness, also improved after the therapy.

Since rhythmic movements were intensively trained during the proposed therapy, the enhancement of all metrics that quantify the performance of these movements was expectable. Discrete movements however, were not trained during the therapy, and behavioural experiments with healthy subjects revealed that no transfer occurs from rhythmic to discrete movements (Ikegami, et al., 2010; Howard, et al., 2011). Thus, a positive evolution of metrics capturing velocity and smoothness in discrete movements was unexpected. Several hypotheses could explain this transfer from rhythmic to discrete movements. First, patients tend to execute rhythmic movements with kinematic features being closer to discrete movements compared to healthy people (Leconte, et al., 2016). Indeed, the harmonicity of the R-T and C-T tasks stayed below the typical level of the healthy control group. Therefore, executing such non-ideal rhythmic movements could facilitate the transition to discrete movements later on. Second, a partial overlap between the neural networks that govern rhythmic and discrete movements could exist, mainly, in the subcortical layers. Again, rhythmic training would then induce plastic neural adaptation that might be beneficial for discrete movements as well.

In contrast, stroke patients did not improve with regards to their accuracy metrics of discrete movements. Accuracy is a hallmark of discrete movements, which typically aim for a specific target (e.g., reaching). Imaging data (Schaal, et al., 2004) showed that even simple discrete movements recruit cortical areas that are thought to play a role in such high level movement planning (Ronsse, et al., 2009; Todorov, 2004), while these area are not recruited during rhythmic movements. Therefore, our results tend to reveal that our rhythmic movement therapy did not leverage the recruitment of these planning circuitries, so that movement accuracy was not exercised, in contrast to velocity and smoothness.

Limitations

The results of this study are promising, since no past research has established the effect of a pure unilateral rhythmic training after stroke. However, this study is not randomized, and the assessors were not blind. Therefore, future RCTs with a larger number of patients are needed.

Testing a larger population would also offer the possibility to test the putative correlation between the reported movement metrics and well-established clinical and/or functional metrics, like e.g. the FMA-UE (Fugl-Meyer, et al., 1975), the modified Ashworth scale (Bohannon & Smith, 1987) capturing elbow flexors muscle spasticity, and (iii) the box and block test (Mathiowetz, et al., 1985). Indeed, previous studies inducing repetitive bilateral arm training with rhythmic auditory cueing (BATRAC) (Whitall, et al., 2000) and resonating arm exercises (RAE) (Zondervan, et al., 2013) reported an improvement in the FMA-UE; and these studies relied on a training intensity being similar to ours.

Finally, we did not include questionnaires such as the ABILHAND (Penta, et al., 2001) or Motor Activity Log (Uswatte, et al., 2006) in our assessment protocol. Such questionnaires aim at assessing the patients' auto evaluation in performing daily motor activities. They provide a complementary viewpoint with respect to the robotic-based metric reported here, since they might capture a perceived change in the capacity to perform smoother movements, possibly with increased endurance. Some verbal testimonies reporting this kind of improvements were informally collected by the experimenter during the therapy, calling thus for a more systematic evaluation of this perception.

Clinical impact

Our results and others (Bütefisch, et al., 1995; Whitall, et al., 2000; Luft, et al., 2004; Stinear & Byblow, 2004; Hesse, et al., 2005; Diserens, et al., 2007; Whitall, et al., 2011) suggest that specific rhythmic movement training should be provided after stroke. Since rhythmic and discrete movements are different motor primitives, both should be trained in order to recover the complete motor repertoire. Moreover, since rhythmic movements are likely easier to be performed by stroke patients (Leconte, et al., 2016), they should be the first movements to train. Discrete movements could then be combined with rhythmic movements, leveraging the execution of movements with a higher degree of impairment to those that are performed more stably (Sternad, et al., 2000; Sternad & Dean, 2003; Leconte, et al., 2016). This second phase of the therapy could thus exclusively focus on the training of the specific discrete features – such as accuracy – while movement smoothness would have already been practiced and improved during the first phase of the therapy, focusing on the rhythmic primitive.

Conclusion

Rhythmic and discrete motor primitives are two fundamental movement classes which are governed at least partially by distinct neural circuitries. This paper specifically explored whether a rhythmic movement therapy offers some benefits to a post-stroke population. A longitudinal pilot study was performed with thirteen patients participating to a one-month rhythmic therapy with the end-effector REAplan robot. Assessments consisted in measuring the kinematics of both rhythmic and discrete movements with the robot. All features (i.e. velocity, smoothness, harmonicity) of the rhythmic movements improved thanks to the therapy. More surprisingly, some discrete movement features, such as velocity and smoothness, also improved after the therapy. Accuracy on the other hand – which is a typical discrete movement feature – was not enhanced through rhythmic movement training. These results amplify the relevance of offering specific rhythmic training to stroke patients, not only to train their own features, but also to trigger improvements for the general motor repertoire, leveraging the excursion of more complex target-oriented discrete movements with repetitive movements being particularly relevant for intensive training.

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Tables

Table I.— Individual features of the post-stroke patients (top) and averaged population data of the patients and control subjects (bottom). FMA-UE stands for “Fugl-Meyer assessment of the upper extremity” (Fugl-Meyer, et al., 1975), i.e. the clinical metric measured during the first assessment session (A1).

Patient	**Gender**	**Dominant hand**	**Paretic Side**	**Age**	**Months post stroke**	**FMA-UE**
1	M	R	R	59	18	56
2	M	R	L	64	23	46
3	M	R	L	60	49	24
4	M	L	L	53	11	18
5	M	R	R	49	14	20
6	F	R	R	58	16	55
7	M	L	L	55	6	55
8	F	R	L	56	10	51
9	F	R	R	51	15	11
10	M	R	L	56	228	44
11	M	R	L	67	126	51
12	M	R	L	66	23	30
13	F	R	R	72	30	37

	Participants (n = 26)	
	Control subjects	**Stroke patients**
Number of participants	13	13
Mean age (SD)	56.15 (5.1)	58.9 (6.7)
Gender (male/female)	4 / 9	8 / 5
Dominant hand (right/left)	12 / 1	11 / 2

Table II.— Overview of the statistics of the metrics for each task. Numbers between brackets report the 95% confidence interval

		mean [95% confidence interval]					*Healthy vs paretic A3*	*A1=A2=A3=A4 ?*		*Stability*	*Short term*		*Long term*	
		A1	*A2*	*A3*	*A4*	Healthy	**p**	*F*	*P*	*A1 vs A2*	*A1 vs A3*	*A2 vs A3*	*A1 vs A4*	*A2 vs A4*
R-T	v_{max}	24,8 [21,31;28,31]	26,6 [23,14;30,14]	31,9 [28,41;35,41]	31 [27,5;24,54]	40,6 [43,5;37,8]	0,08	F(3;361,2)=29,17	**<0.0001**	0.17	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
	H	0,15 [-0,01;-0,3]	0,2 [0,03;0,35]	0,36 [0,21;0,52]	0,32 [0,17;0,48]	0,66 [0,74;0,59]	**0,032**	F(3;361,2)=18,5	**<0.0001**	0,45	**<0.0001**	**<0.0001**	**<0.0001**	**0,0014**
	$DWELL$	0,08 [0,001;0,15]	0,08 [0;0,14]	0,01 [-0,05;0,085]	0 [-0,07;0,07]	0 [0;0]	0,15	F(3;362,1)=2,6	0,051					
	$SPARC$	-1,64 [-1,7;-1,58]	-1,63 [-1,69;-1,57]	-1,56 [-1,62;-1,5]	-1,56 [-1,63;-1,51]	-1,56 [-1,54;-1,57]	0,99	F(3;361,6)=7,5	**<0.0001**	0,96	**0,001**	**0,005**	**0,005**	**0,023**
C-T	v_{max}	17,2 [14,34;20,07]	18,2 [15,30;21,02]	23,8 [20,90;26,62]	24,8 [21,93;27,68]	34,95 [36,9;33]	**0,002**	F(3;361,2)=64,77	**<0,0001**	0,47	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
	H	0,14 [0,06;0,23]	0,08 [0;0,16]	0,3 [0,21;0,38]	0,29 [0,21;0,38]	0,63 [0,68;0,57]	**0,0015**	F(3;361,4)=35,94	**<0,0001**	0,056	**<0,0001**	**<0,0001**	**<0,0001**	**<0,0001**
	$DWELL$	0,31[0,14;0,47]	0,19 [0,02;0,35]	0,02 [-0,15;0,18]	0,01 [-0,16;0,17]	0 [0;0]	0,17	F(3;362,1)=6,5	**0,0002**	0,41	**0,0015**	0,14	**0,0012**	0,11
	$SPARC$	-1,79 [-1,93;1,65]	-1,81 [-1,96;-1,68]	-1,57 [-1,71;-1,43]	-1,56 [-1,7;-1,41]	-1,54 [-1,53;-1,55]	**0,005**	F(3;362,2)=7,8	**<0,0001**	0,98	**0,0072**	**0,0022**	**0,0067**	**0,0021**
C-NT	v_{max}	19,57 [16,67;22,47]	19,7 [16,81;22,59]	25,37 [21,47;27,26]	23,52 [20,62;26,42]	33,18 [35,5;30,9]	**0,0244**	F(3,353,4)=33,5	<0,0001	0,9968	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
	H	0,3 [0,16;0,43]	0,19 [0,06;0,33]	0,41 [0,28;0,54]	0,27 [0,14;0,41]	0,48 [0,54;0,41]	0,59	F(3,353,4)=17,7	<0,0001	**0,0074**	**0,001**	**<0.0001**	0,92	**0,048**
	$DWELL$	0,02 [0;0,04]	0,03 [0;0,05]	0,00[-0,02;0,03]	0,008[-0,02:0,03]	0 [0;0]	0,33	F(3,357,3)=1,25	0,29					
	$SPARC$	-1,6 [-1,66;-1,56]	-1,63 [-1,68;-1,58]	-1,58 [-1,63;-1,53]	-1,57 [-1,63;-1,53]	-1,53 [-1,53;-1,54]	**0,0001**	F(3,356,6)=1,6	0,18					
R-NT	v_{max}	27,7[23,98;31,33]	25,4 [21,59;28,94]	32,3 [28,65;35,99]	32 [28,34;35,74]	36,5 [38,8;34,3]	0,27	F(3;361,3)=24,15	**<0,0001**	0,07	**<0.0001**	**<0.0001**	**0,0001**	**<0.0001**
	H	0,27 [0,13;0,42]	0,22[0,07;0,37	0,43 [0,29;0,58]	0,33 [0,19;0,48]	0,5 [0,57;0,43]	0,58	F(3;361,3)=11,1	**<0,0001**	0,53	**0,0003**	**<0.0001**	0,41	**0,02**
	$DWELL$	0,001 [-0,006;0,009]	0,01 [0,008;0,023]	0 [-0,008;0,008]	0 [-0,008;0,008]	0 [0;0]	*	F(3;364,5)=3,77	0,1					
	$SPARC$	-1,61 [-1,65;-1,56]	-1,61 [-1,66;-1,56]	-1,55 [-1,6;-1,5]	-1,57 [-1,61;-1,52]	-1,57 [-1,56;-1,59]	0,39	F(3,361,4)=8,14	**<0,0001**	0,98	**0,0015**	**0,0003**	**0,0299**	**0,0095**
D-T	v_{max}	17,35 [15,63;19,07]	17,94 [16,22;19,67]	20,79 [19,07;22,5]	20,73 [19,00;22,47]	17,1 [18,2;16]	0,054	F(3;355,3)=13,58	**<0,0001**	0,83	**<0,0001**	**0.0003**	**<0,0001**	**0,0006**
	H	0,001 [0;0,01]	0,005 [0,001;0,008]	0,003 [0;0,007]	0,001 [-0,003;0,004]	0,03 [0,05;0,01]	0,16	F(3;358) = 1,29	0,28					
	$DWELL$	0,77 [0,34;1,2]	0,86 [0,42;1,29]	0,55 [0,12;0,98]	0,69 [0,25;1,12]	0,14 [0,19;0,08]	**0,0124**	*F(3;355,3)=1,5*	0,21					
	$SPARC$	-1,98 [-2,23;-1,72]	-1,87 [-2,13;-1,62]	-1,71 [-1,97;-1,47]	-1,64 [-1,9;-1,39]	-1,55 [-1,54;-1,58]	**0,0057**	F(3;355,3)=6,4	**0,0003**	0,59	**0,0088**	0,233	**0,0006**	**0,038**
	$accuracy$	1,22 [0,91;1,54]	0,77 [0,46;1,09]	0,71 [0,4;1,03]	0,64 [0,33;0,97]	0,41 [0,46;0,36]	**0,0009**	F(;,355,9)=7,59	**<0,0001**	**0,005**	**0,0008**	0,96	**0,0002**	0,79
D-BT	v_{max}	20,12 [17,65;22,58]	21,61 [19,13;24,08]	23,9 [21,46;26,35]	25,08 [22,59;27,57]	27,8 [29,6;26]	0,21	F(3;336,1)=15,64	**<0,0001**	0,24	**<0,0001**	**0,018**	**<0,0001**	**0,0002**
	$SPARC$	-1,62 [-1,68;-1,57]	-1,61 [-1,67;-1,55]	-1,55 [-1,6;-1,49]	-1,55 [-1,61;-1,49]	-1,53 [-1,51;-1,55]	0,56	F(3;335,7)=13,95	**<0,0001**	0,7	**<0,0001**	**0,0003**	**<0,0001**	**0,0014**
	$accuracy$	1,62 [1,31;1,95]	1,73 [1,41;2,05]	1,35 [1,04;1,67]	1,54 [1,2;1,86]	0,94 [1,05;0,84]	**0,0091**	F(3,337,4)=2,33	0,064					

Legends for illustrations

Figure 1.— Panel A: The REAplan end-effector robot used during this study. Panel B: Robotic assessment tasks. The participants performed four rhythmic and two discrete tasks during the robotic assessment sessions. Panel C: tasks executed by the patients during the therapy while receiving robotic assistance. Distance D was determined as a function of the patient's performance during the initial short assessment phase at the beginning of each session. It could vary from 2cm to 15cm.

Figure 2.— Assistance forces that can be provided to the patient if needed, illustrated for a circular movement. A. The smoothness assistance $F_{smoothness}$ is rendered by a virtual spring between the actual position of the patient p_{pat} and its smoothed version p_{osc}. B. The velocity assistance $F_{velocity}$ is a longitudinal force pulling the patient forward. C. The amplitude assistance $F_{amplitude}$ provides a radial force in order to help the patient to reach higher amplitudes.

Figure 3.— Evolution over the 4 assessment days (A1, A2, A3 and A4) and the assessment of healthy subjects (H) during rhythmic tasks (R-T – left – and C-T – right) in, respectively, the (a) velocity, (b) harmonicity, and (c) $SPARC$ metrics. The error bars represent the 95% confidence intervals. The horizontal lines above the different panels capture the assessment numbers being significantly different from each other. When the healthy data were significantly different from the third assessment of the paretic arms A3, a star (*) is displayed above the healthy result.

Figure 4.— Evolution over the 4 assessment days (A1, A2, A3 and A4) and the assessment of healthy subjects (H) during discrete tasks (D-T – left – and D-BT – right) in, respectively, the (a) velocity, (b) accuracy, and (c) $SPARC$ metrics. The error bars capture the 95% confidence interval. The horizontal lines above the different panels capture the assessment numbers being significantly different from each other. When the healthy data were significantly different from the third assessment of the paretic arms A3, a star (*) is displayed above the healthy result.

Figure 1

Click here to access/download;Figure;IJRR_Ronsse_fig1.jpeg

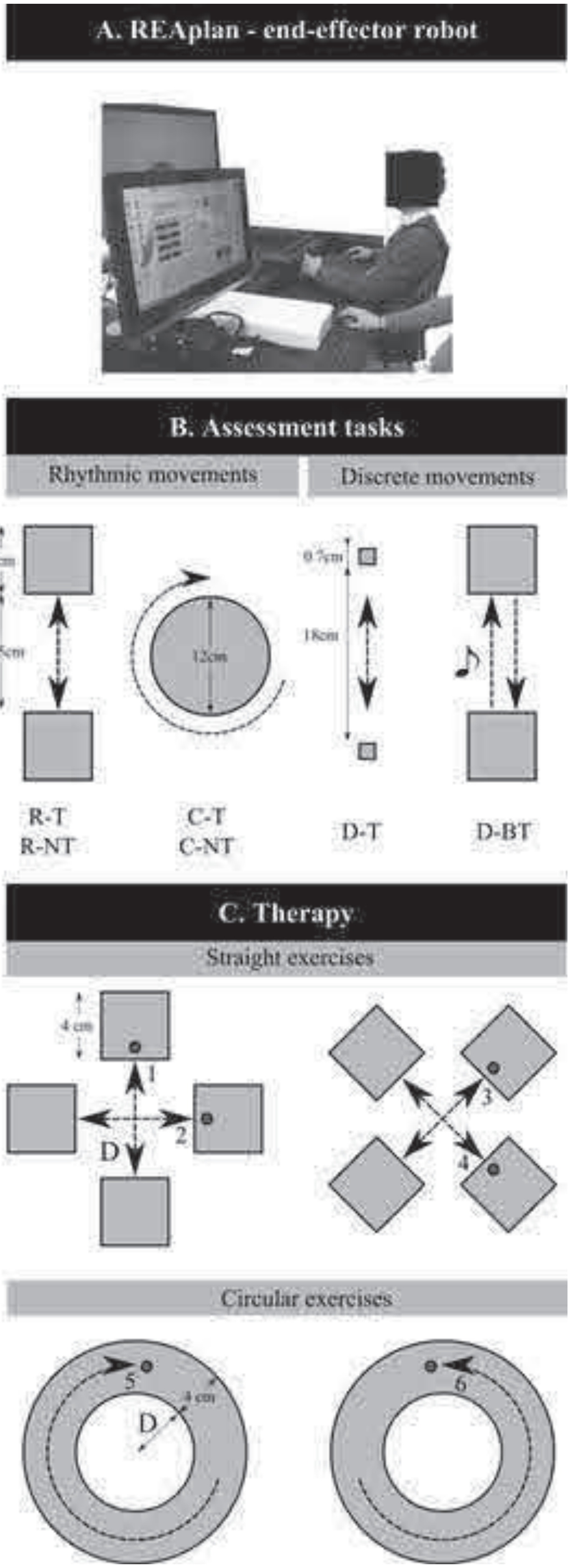
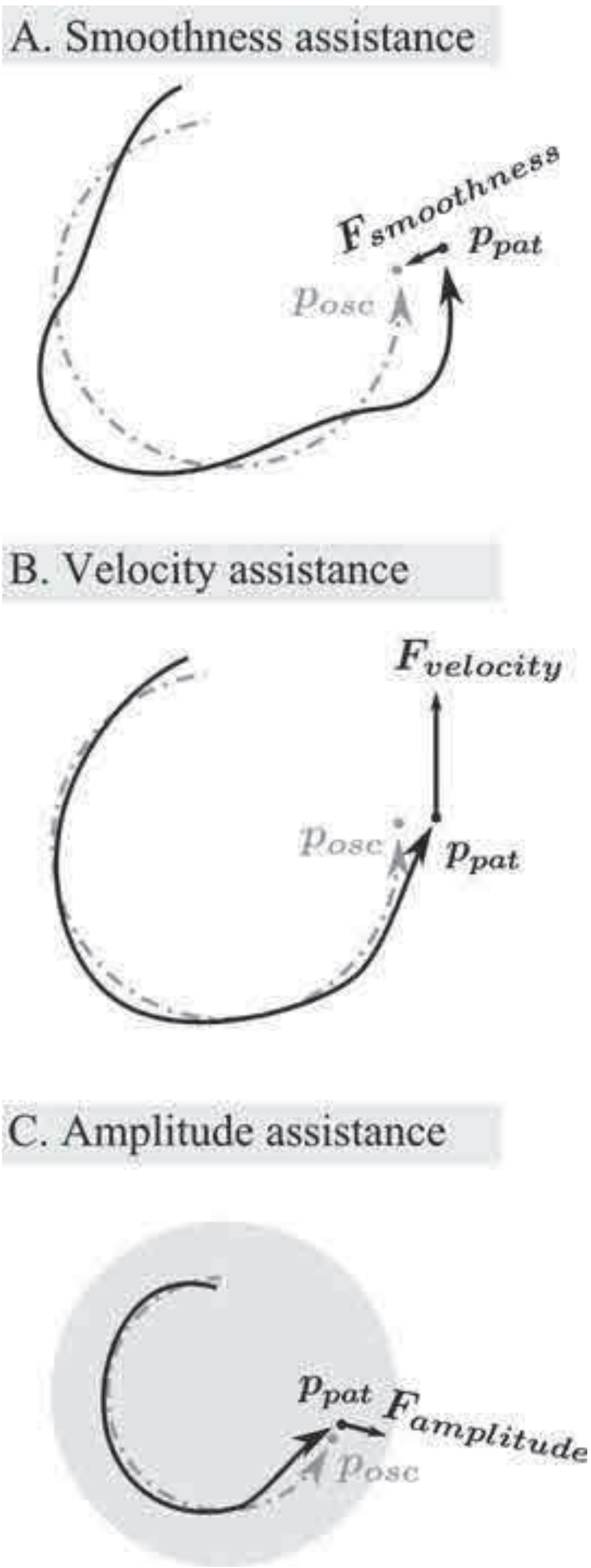


Figure 2 Click here to access/download;Figure;IJRR_Ronsse_fig2.jpeg



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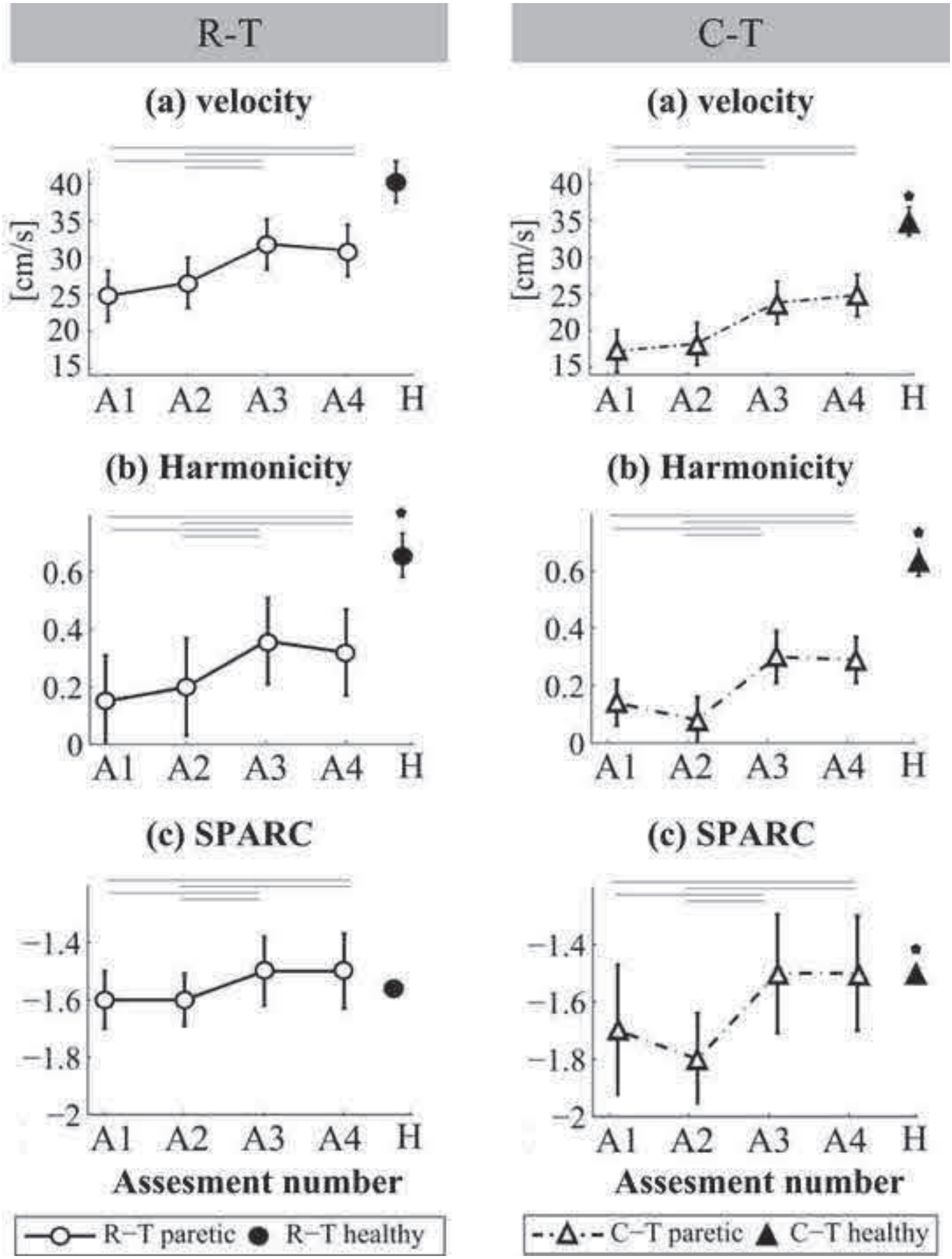

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